SOBA 3: SEDIMENTS & GEOMORPHOLOGY

AYEYARWADY STATE OF THE BASIN ASSESSMENT (SOBA)

Status: Final
Last updated: 29/10/2017
Prepared by:
World Wide Fund for Nature (WWF) Greater Mekong

Disclaimer
"The Ayeyarwady State of the Basin Assessment (SOBA) study is conducted within the political boundary of Myanmar, where more than 93% of the Basin is situated."

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ACKNOWLEDGEMENTS

SOBA 3 was completed under contract to WWF Greater Mekong. The project team included the following members:

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The SOBA 3 Team would like to thank the following individuals and organizations for their assistance during completion of this project: the SOBA Project Management Unit for assistance and advice before and during the project; the other SOBA teams for feedback, information, and advice; WWF Myanmar for administrative, logistical, and field support; the WWF Helmsley Project and Edward Anthony and his team for assistance and information pertaining to the delta; and the crew of the RV Mingun for providing invaluable assistance during the field investigations.

DISCLAIMER

This document was prepared for the Directorate of Water Resources and Improvement of River Systems (DWIR), Project Management Unit (PMU) by a consultant team engaged to undertake the technical assistance project 'C1.13 - State of the basin report package 3 – Sediments and Geomorphology'. The views, conclusions and recommendations in the document are not to be taken to represent the views of DWIR or PMU. The Ayeyarwady State of the Basin Assessment (SOBA) study is conducted within the political boundary of Myanmar, where more than 91% of the Basin is situated. The maps contained within this report delineate the Ayeyarwady based on political rather than natural catchment boundaries, however, all analysis and discussion contained within this report is based on the natural catchment boundaries of the river. Understanding the impact of activities outside of Myanmar on the Ayeyarwady is critical for an accurate geomorphic understanding of the river and for identifying a sustainable development pathway.

Prepared by	WWF Greater Mekong
Prepared for	Ministry of Transport and Communications, DWIR, Ayeyarwady Integrated River Basin Management (AIRBM) project, PMU.
Suggested Citation	WWF (2017). *C1.13 - State of the basin report package 3 – Sediments and Geomorphology, Draft Final Report*. Prepared for DWIR, PMU.
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LIST OF ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
AIRBM	Ayeyarwady Integrated River Basin Management
CM	Sediment analysis technique using the 99th percentile grain-size of a sediment sample (C denotes coarsest fraction) and Median (M) grain-size
cm	centimetre
cm yr^{-1}	cm per year
DMH	Department of Meteorology and Hydrology
DWIR	Directorate of Water Resources and Improvement of River Systems
FAO	Forest and Agriculture Organization
GDEM	Global Digital Elevation Model
GIS	Geographic Information System
GMS	Greater Mekong Subregion
GPS	Global Positioning System
ha	hectare
HEZ	Hydro-Ecological Zone
ICEM	International Centre for Environmental Management
IFC	International Finance Corporation
km^2	square kilometre
km^2yr^{-1}	square kilometre per year
km^3	cubic kilometre
m	metre
mg L^{-1}	milligram per liter
mm	millimetre
mm $month^{-1}$	millimetre per month
m^3	cubic metre
m^3s^{-1}	cubic metre per second
MOEE	Ministry of Electricity and Energy, Myanmar

MONREC	Ministry of Natural Resources and Environmental Conservation
m s^{-1}	metres per second
Mt yr^{-1}	million tonne per year
MW	megawatt
PMU	Project Management Unit
SOBA	State of the Basin Assessment
SOBA 3	State of the Basin Assessment 3: Sediments and Geomorphology
SRTM	Shuttle Radar Topography Mission
SSC	Suspended sediment concentrations (based on a depth integrated water sample)
t day^{-1}	tonne per day
t $km^2 yr^{-1}$	tonne square kilometres per year
TSS	total suspended solids (based on a water sample collected from the surface)
WISDM	Water Information System for Data Management
WWF	World Wide Fund for Nature

LIST OF GEOMORPHIC TERMS

Main stem	The primary segment of a river as compared to its tributaries. The Ayeyarwady main stem is defined as starting at the confluence of the Mali Hka and N'mai Hka Rivers. Upstream of this confluence the N'mai Hka and Mali Hka each have their own main stems.
Left bank	The left side of the river when facing downstream.
Right bank	The right side of the river when facing downstream.

EXECUTIVE SUMMARY

The Ayeyarwady Integrated River Basin Management (AIRBM) Project is developing a State of the Basin Report for the Ayeyarwady River (SOBA). The aim of AIRBM is to provide Myanmar with relevant and accurate information for use in implementing integrated basin management in the Ayeyarwady. The SOBA component of the project is to provide an accurate and up to date baseline of the catchment capturing the existing conditions and historic trends of the key characteristics of the river basin, and how the people of Myanmar use and benefit from the resources of the river. SOBA Package 3 is focused on the Sediments and Geomorphology of the Ayeyarwady and the aims of the work package include:

- Assess the status and trends of key characteristics of the basin's geomorphology and sediment dynamics;
- Analyse these trends to assess their implications for the Ayeyarwady system; and,
- Recommend a conceptual design for a sediment and geomorphic monitoring program on the Ayeyarwady River.

The SOBA Package 3 team has addressed these aims by gaining an understanding of the river and its catchment at a range of scales, by identifying the linkages between land and river uses, and by identifying appropriate indicators to establish the present condition, explore historic trends, and project future trends within the river system. Other outcomes of the investigations include the proposal for a comprehensive sediment monitoring strategy within the context of a larger land use monitoring strategy.

The character of the Ayeyarwady River is strongly dependent on the geological and tectonic features of Myanmar. The river catchment is developed on the active collision zone between the Indian Plate to the west and the Eurasian Plate to the east, with the course of the river, sediment types and sediment input rates all influenced by this unique setting. The northern half of the Ayeyarwady catchment is roughly divided in half by the active Sagaing fault. East of this collision zone, the geology is characterised by older resistant crystalline igneous and metamorphic rocks, including the Shan Plateau, the southernmost extension of the Tibet Plateau. West of the Sagaing fault the geology consists of relatively young thrusted and faulted rocks where high rainfall has led to deep weathering of the tectonically weakened strata. This area is drained predominantly by the Chindwin River, the largest tributary of the Ayeyarwady, and a major contributor to the sediment load of the basin. Downstream of the confluence the river continues to flow through this 'western' style geology before reaching the wedge-shaped, flat laying depositional Ayeyarwady delta.

The variability of rainfall in the Ayeyarwady exerts a strong control on the geomorphic processes operating in the system. In the headwaters and along the western ranges of the Chindwin monsoonal, rainfall patterns dictate the flood-pulse flow pattern of the system. In the lower Chindwin and lower Ayeyarwady, rainfall is much lower due to the area being in a rain shadow, but the episodic high rainfall events that do occur are important for transporting large volumes of sediment from this arid landscape to the rivers. The characteristics of the river system were used to identify geomorphic zones, within which sediment transport processes are considered to be similar (

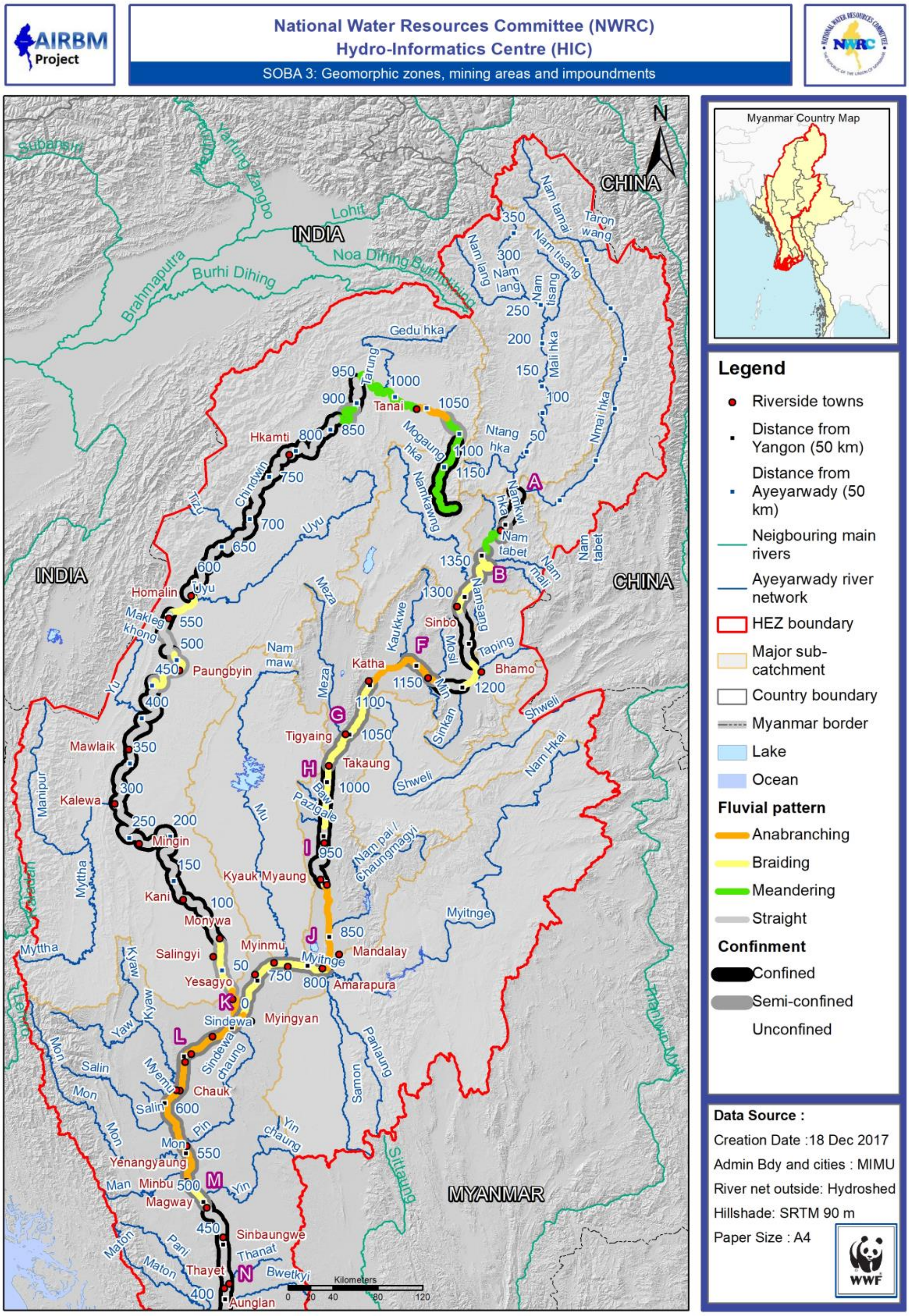

Figure 1.3).

The characteristics of the Ayeyarwady River include steeply sloping headwater and tributary rivers, but an overall low, although variable, slope of the river downstream of the confluence of the Nmai Hka and Mali Hka. The width of the Ayeyarwady reflects the landscape, with predominantly broad alluvial valleys joined by single channel reaches where it cuts through resistant strata. The variability in river slope and valley width combines to control the transport and deposition of sediment along the river, and accounts for areas of the river in which sediment reworking and active channel migration occur.

An analysis of braiding patterns in different sections of the river found varying trends in channel behaviour. Zones 'J' and 'K', located in the middle Ayeyarwady where hydropower development and land use changes have altered sediment inputs and flow patterns to a higher degree as compared to other areas show decreasing trends in channel braiding, whereas zone 'G' located upstream of the Sagaing Fault zone and zone 'L' located downstream of the Chindwin show increasing trends. These results highlight how different river reaches can respond differently to the same catchment conditions, and underscores the need for a reach-by-reach understanding of the river for management.

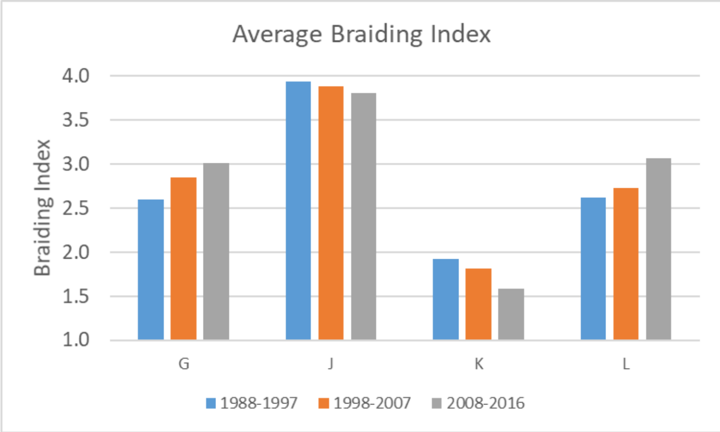
Average Braiding Index
Braiding Index
4.0
3.5
3.0
2.5
2.0
1.5
1.0
G
J
K
L
1988-1997
1998-2007
2008-2016

Figure 1.1 - Braiding Index for four river reaches in the Ayeyarwady *(zones indicated in*

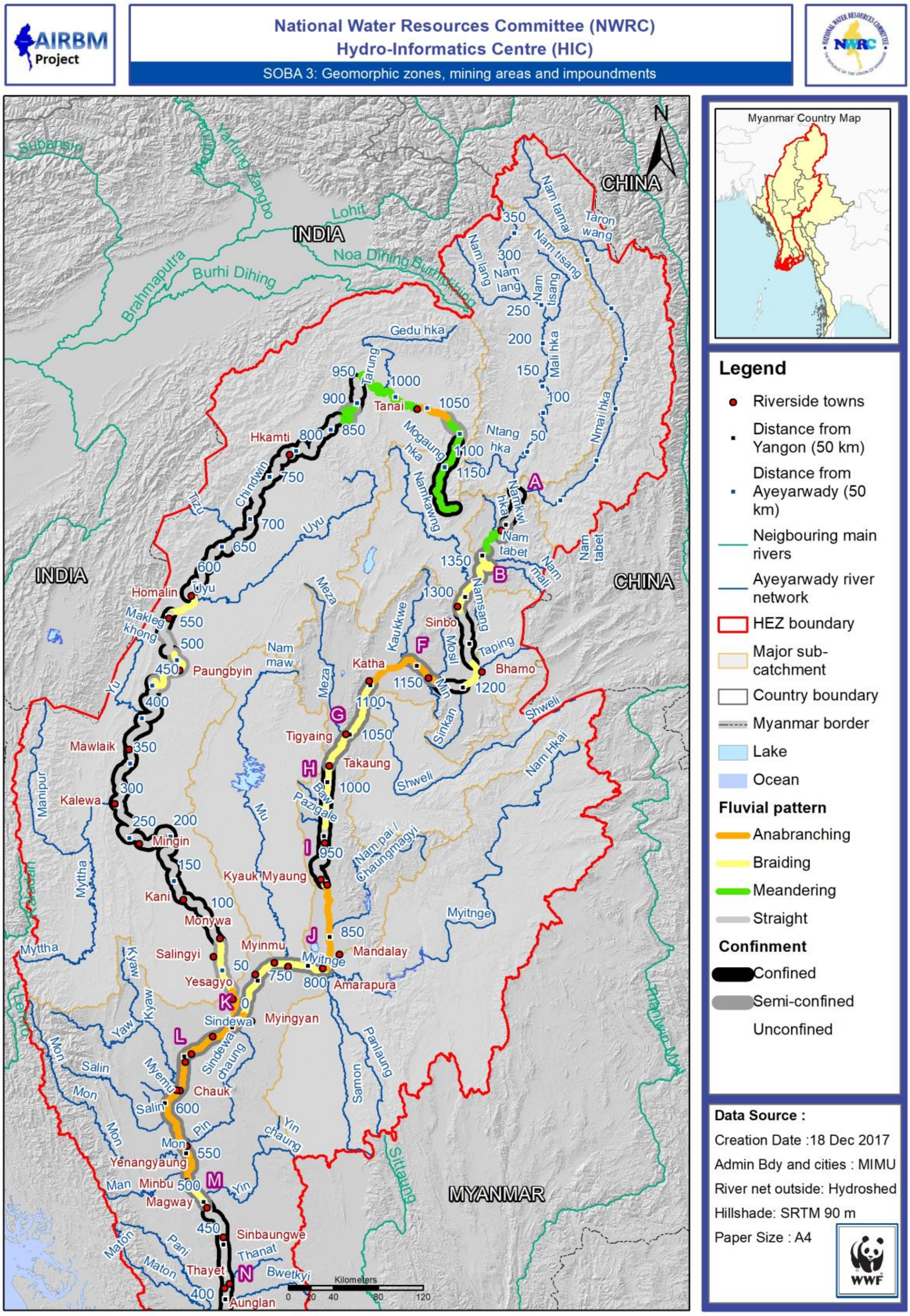

Figure 1.3)

Land and river developments affect the geomorphology of rivers by altering the pattern and / or quantity of flow and sediment entering the river. The SOBA 3 team identified and quantified land use changes associated with deforestation, mining, hydropower, irrigation and sand and gravel extraction in the Ayeyarwady. Deforestation and terrestrial mining can increase sediment inputs to rivers due to land disturbance. Large areas of the Ayeyarwady have been, and continue to be affected by these activities, and observations made by SOBA 3 suggest there is a high likelihood that the characteristics and volumes of sediment entering the river are being altered by these activities.

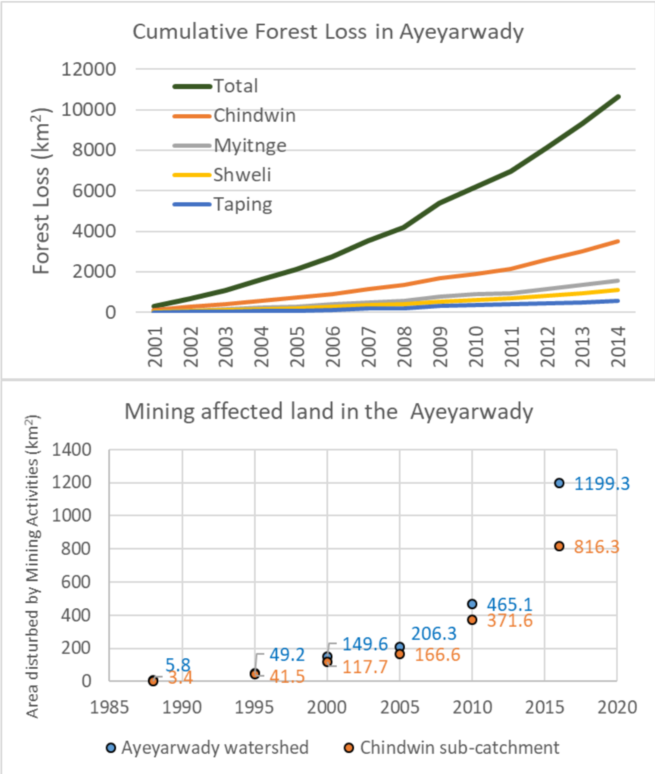

Figure 1.2 - (top) Rates of deforestation and (bottom) rates of land disturbance associated with mining activities are increasing in the Ayeyarwady. (*Forestry based on Hansen et al., 2013, mining derived from satellite image analysis completed by SOBA Package 3.)*

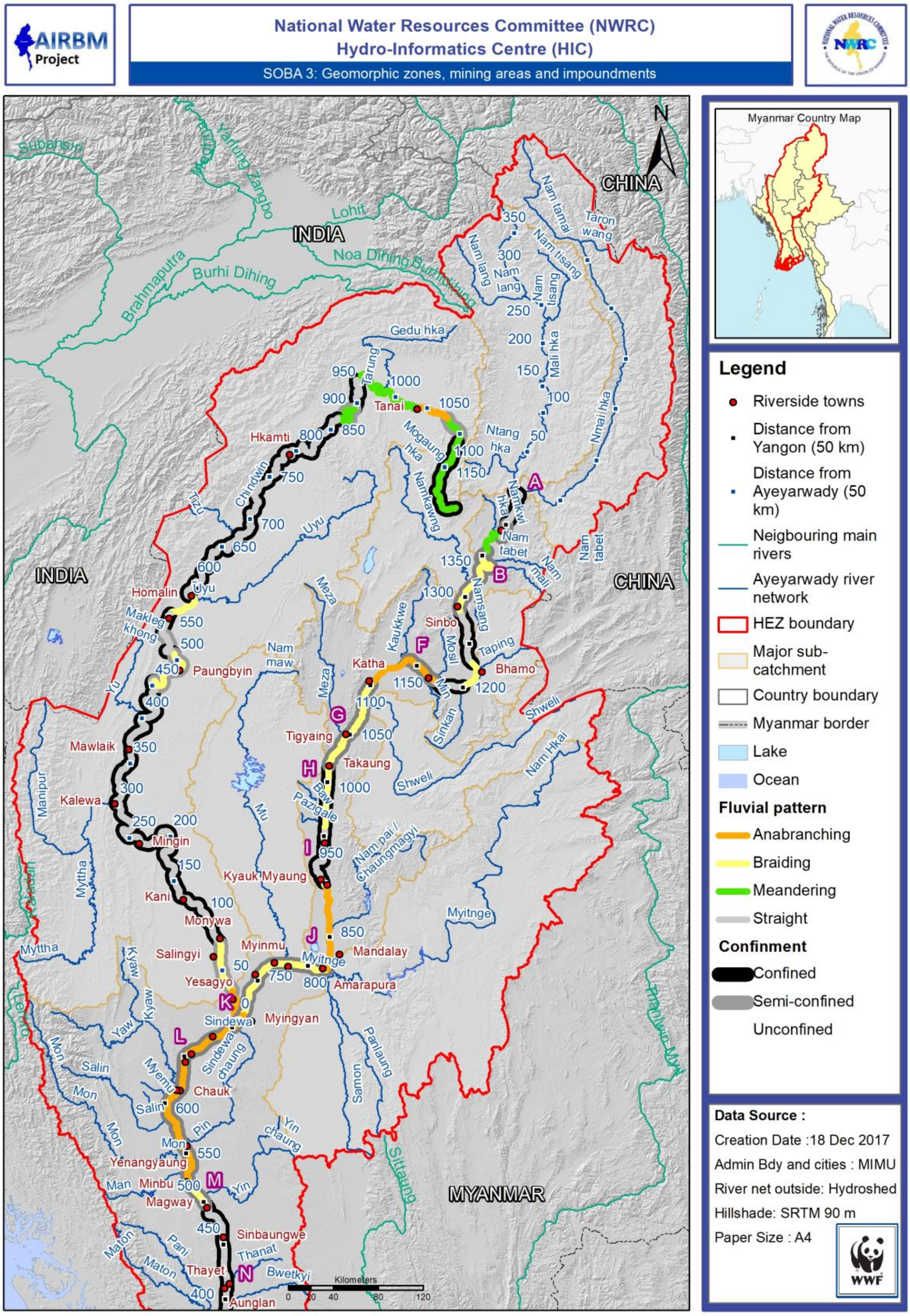

Figure 1.3 - Channel characteristics in the Ayeyarwady and Chindwin Rivers and geomorphic zones in the Ayeyarwady based on channel attributes

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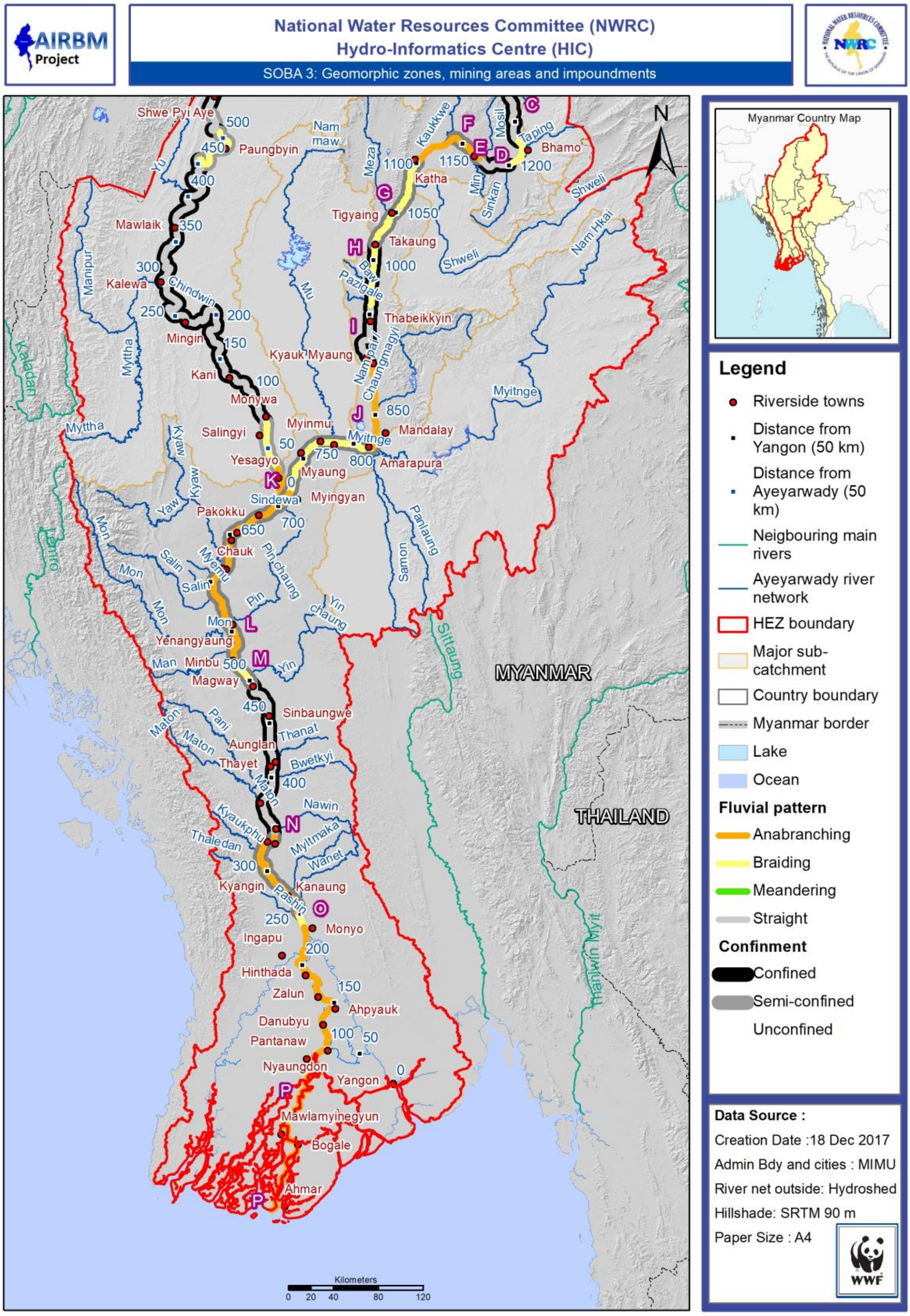
AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones, mining areas and impoundments
Myanmar Country Map
Legend
Riverside towns
Distance from Yangon (50 km)
Distance from Ayeyarwady (50 km)
Neigbouring main rivers
Ayeyarwady river network
HEZ boundary
Major sub-catchment
Country boundary
Myanmar border
Lake
Ocean
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
Confinment
Confined
Semi-confined
Unconfined
Data Source :
Creation Date :18 Dec 2017
Admin Bdy and cities : MIMU
River net outside: Hydroshed
Hillshade: SRTM 90 m
Paper Size : A4
WWF
Kilometers
0 20 40 80 120
N
MYANMAR
THAILAND
Shwe Pyi Aye
Paungbyin
Mawlaik
Kalewa
Mingin
Kani
Monywa
Salingyi
Yesagyo
Myinmu
Myaung
Sindewa
Myingyan
Pakokku
Chauk
Salin
Yenangyaung
Minbu
Magway
Sinbaungwe
Aunglan
Thayet
Kyangin
Monyo
Ingapu
Hinthada
Zalun
Ahpyauk
Danubyu
Pantanaw
Nyaungdon
Yangon
Mawlamyinegyun
Bogale
Ahmar
Mandalay
Amarapura
Kyauk Myaung
Thabeikkyin
Takaung
Tigyaing
Katha
Bhamo
Chindwin
Sittaung
Thanlwin Myit
Shweli
Nam Hkai
Myitnge
Panlaung
Samon
Mu
Kaladan
Myittha
Manipur
Yu
Taping
Mosit
Sinkan
Kaukkwe
Meza
Nampai
Chaungmagyi
Pazigale
Pin
Yin
Pinchaung
Mon
Man
Pani
Maton
Thanat
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Tenasserim
Nam maw

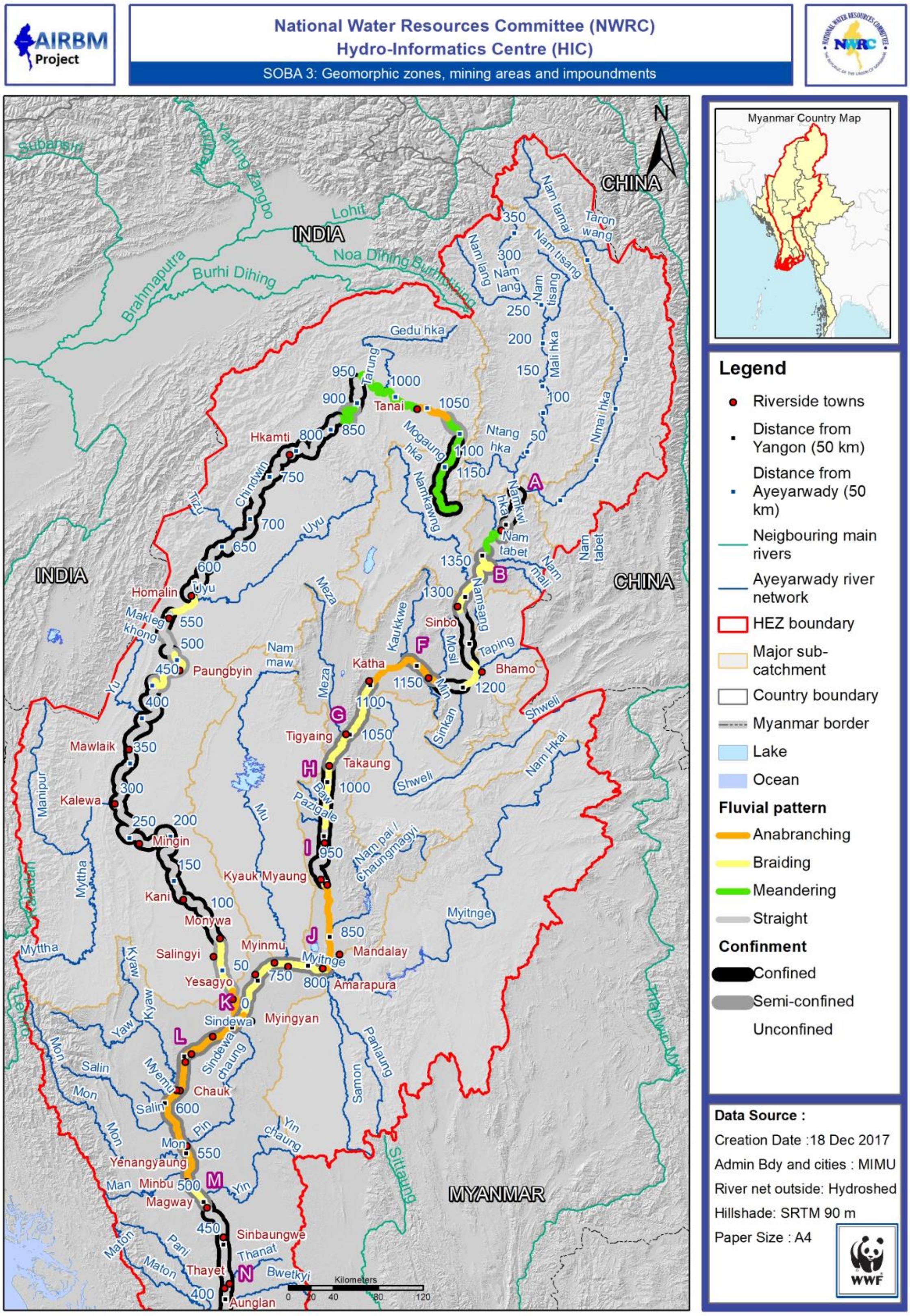


Figure 1.3 - Channel characteristics in the Ayeyarwady and Chindwin Rivers and geomorphic zones in the Ayeyarwady based on channel attributes

Hydropower and irrigation activities can change the flow regime of rivers and affect sediment budgets by reducing sediment inputs and altering sediment transport patterns. The present scale of these activities is likely to be be modifying the f flows and reducing the sediment loads, as evidenced by geomorphic changes to the channel characteristics of tributaries. Present hydropower development is largely focused in the upper Ayeyarwady, with irrigation developed in the lower basin. The relative impact of these activities was not possible to determine due to a lack of information regarding irrigation impoundments and operating regimes.

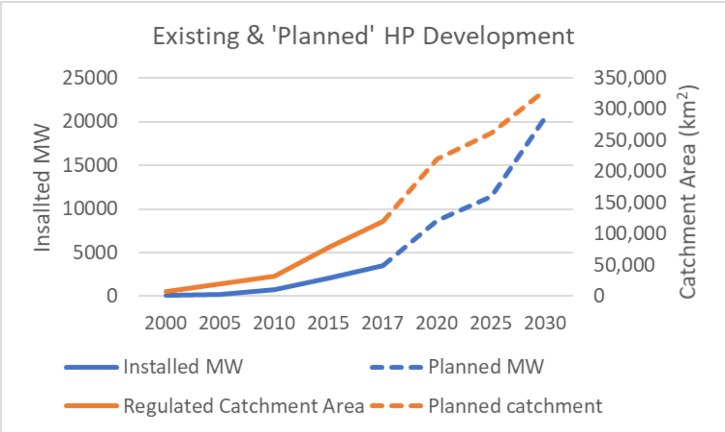


Figure 1.4 - Existing and 'planned' hydropower projects in the Ayeyarwady
(Source: IFC, MOEE and MONREC, 2017)

Satellite image analysis was combined with ground based surveying of sand and gravel distributors to ascertain the locations, methods, and volumes of construction materials extracted from the river. The investigations focused on the lower river near large population centres, and documented extraction rates of about 10 million tonnes per year (Mt yr^{-1}) of sand and gravel based on the responses of the survey participants. The actual volumes extracted are higher than this value due to the large number of operators not included in the survey (including the entire river upstream of Mandalay/Sagaing) and the number of operators who did not report volumes. A 'back of the envelope' comparison of possible bedload volumes being transported by the river suggests that extracting 10 to 20 or more Mt of material per year from the river carries a high risk of having a geomorphic impact on the system. The recent concerns expressed by local communities about riverbank erosion in areas exploited for sand and gravel mining are consistent with these findings, as are recent delta investigations concluding that the resilience of the delta may be decreasing with increasing erosion recorded near the mouths of the distributaries (Edward *et al.*, 2017).

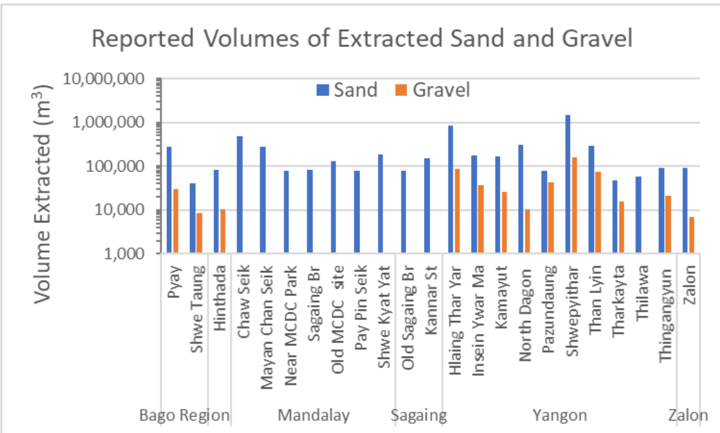


Figure 1.5 - Summary of volumes of sand and gravel extracted from different areas based on survey results

Field observations and investigations documented the grain-size characteristics of sediment moving through the system, and identified key areas of sediment input, transport, and deposition. The Ayeyarwady is not only a flood-pulse system with respect to flow, but is also a sediment-pulse system. The investigations found that the alluvial banks of the river are dominated by fine to medium sand and the bed of the river is dominated by medium to coarse sand. There is a general trend of sediment size coarsening (increasing) downstream, which is unusual in rivers. Based on field observations and the sediment data, it is suggested that the increased presence of coarse sand and gravel is attributable to sediment input from the Sagaing fault zone, where mining activities have altered the landscape and sediment budgets of the tributaries, and from the lower Ayeyarwady in the Dry Zone, where episodic high rainfall events are likely to transport large volumes of material from the arid exposed landscape. Coarse-grained inputs from the Chindwin are also likely, but the sediment results did not reflect a major shift in grain-size immediately downstream of the confluence.

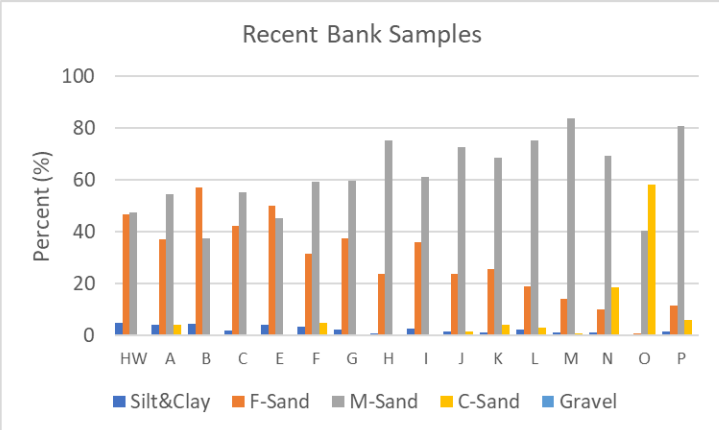
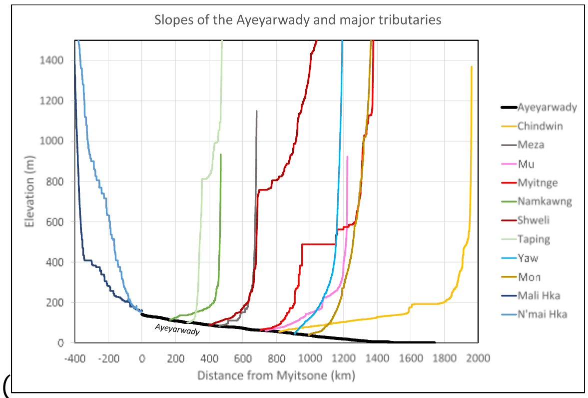


Figure 1.6 - Grain-size distribution of active alluvial banks in the Ayeyarwady.
F=Fine, M=Medium, C=Coarse.

A conceptual model of sediment transport includes these episodic inputs of high volumes of sediment overlain on the more continual input of sediments from the high rainfall areas of the Ayeyarwady and Chindwin headwaters. These processes can be compared to conveyor belts moving at different speeds, with rapid and episodic input from tributaries combining with the slow, more continuous movement through the Ayeyarwady. Within the Ayeyarwady, the speed of the 'conveyor belt' also varies due to the variability in



river slope (

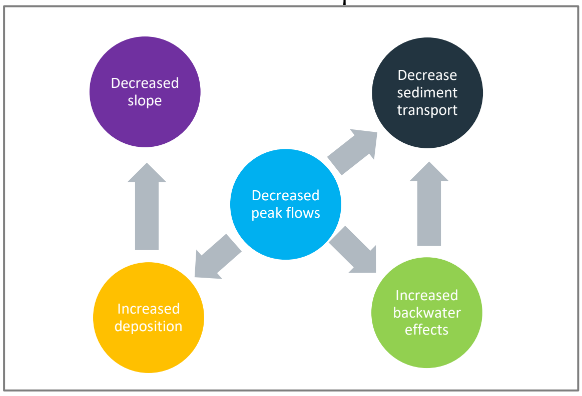
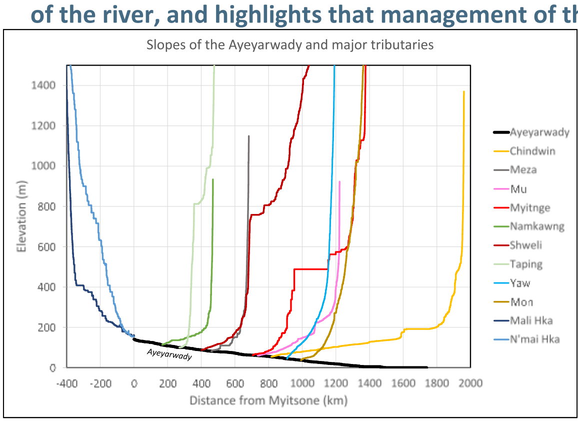


Figure 1.7). Sediment pulses can be readily transported through some areas of the river, but become stored in other areas. This is especially relevant when land use activities such as mining produce coarse-grained sediments that require high river energy for transport, thus limiting the window for these materials to move through the system at peak flow times. The progressive implementation of hydropower and irrigation impoundments that have the potential to reduce these peak flow periods pose long-term risks to sediment transport in the river. In turn, areas that become 'choked' with sediment can experience bed aggradation and high rates of channel migration, and bank erosion. Understanding the inseparable linkages between land use, sediment characteristics and transport is fundamental to the long-term sustainable management of the river, and highlights that management of the river is contingent on management of the land (



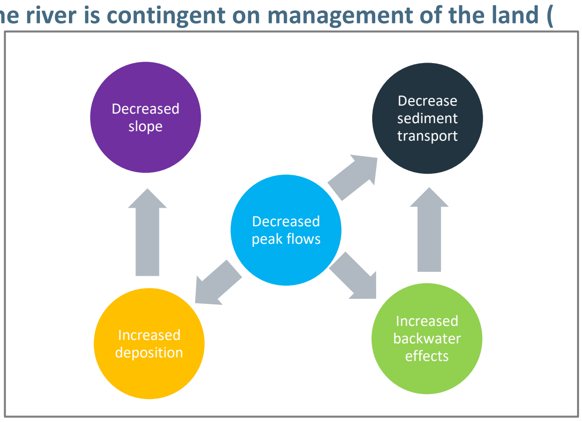


Figure 1.7).

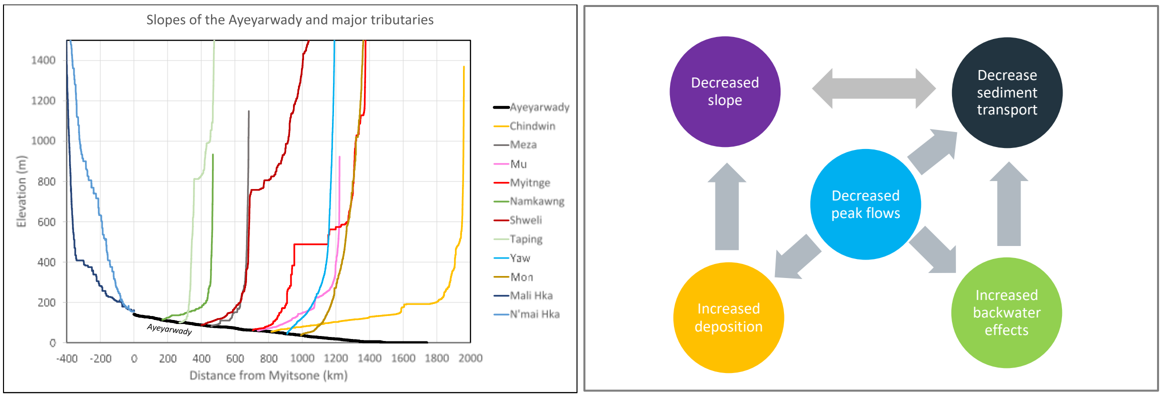


Figure 1.7 - Slope of the Ayeyarwady (solid dark line) and major tributaries, and potential feedback mechanisms leading to increased deposition in the river channel

Fine-grained sediment loads were estimated based on Total Suspended Solids (TSS) values collected during the field investigations. The results were very low (<40,000 tonnes per day [t day^{-1}];

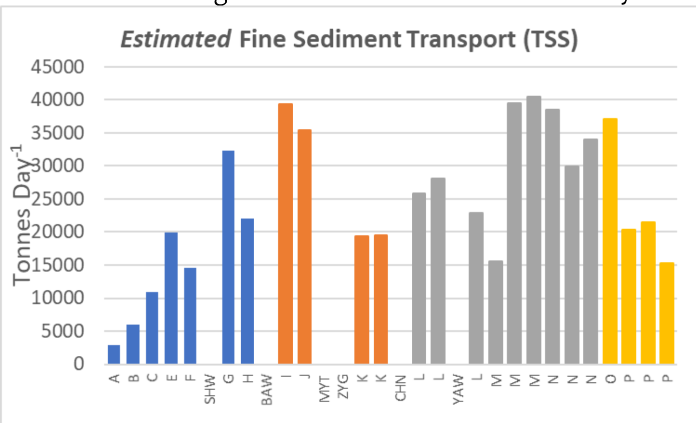


Figure 1.8), but consistent with the lowest values recorded by Gordon in the 1880s (Stamp, 1940), although the 2017 flows were higher, and concentrations were lower than the historic results. A hypothetical sediment budget for fine- and coarse-grained sediments was derived based on the characteristics and distribution of physiographic/geomorphic units in the basin. The constraints used to derive the budget were based on quantitative assessments of the provenance of sand in the system (Garzanti *et al.*, 2016), historic observations (Stamp, 1940) and published estimates of sediment yields from similar river catchments (Milliman and Syvitski, 1992). The land units assumed to be the major sediment inputs included the steep slopes (>10°) in the crystalline strata east of the Sagaing fault and the easily erodible hills in the western Chindwin and lower Ayeyarwady River. Lower sediment yields (400 to 600 tonne square kilometres per year [t km^{2}yr^{-1}]) were assigned to lower sloped units. A reasonable fit to the constraints was achieved with an overall sediment budget of ~220 Mt yr^{-1}, with about half of the sand derived from the upper Ayeyarwady, and the remaining input split between the Chindwin and the lower Ayeyarwady. A little less than half of the silt was derived from the Chindwin, with about 25% sourced from the upper Ayeyarwady. The exercise highlights the different sediment yields required to satisfy the field observations and data regarding the provenance and abundance of silt in the Chindwin. These values should not be considered accurate as the derivation of a reliable sediment budget suitable for use in management requires accurate and long-term monitoring of the river.

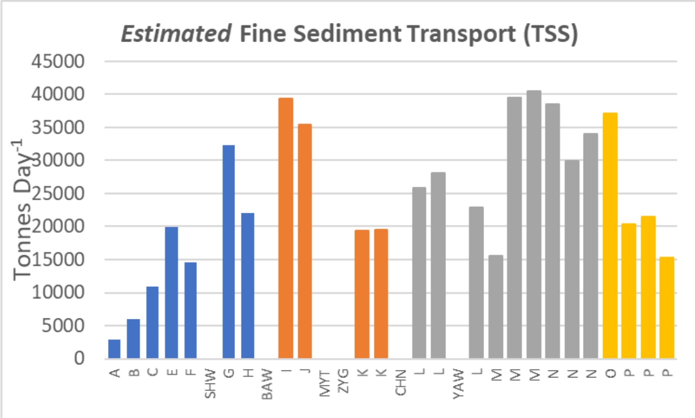
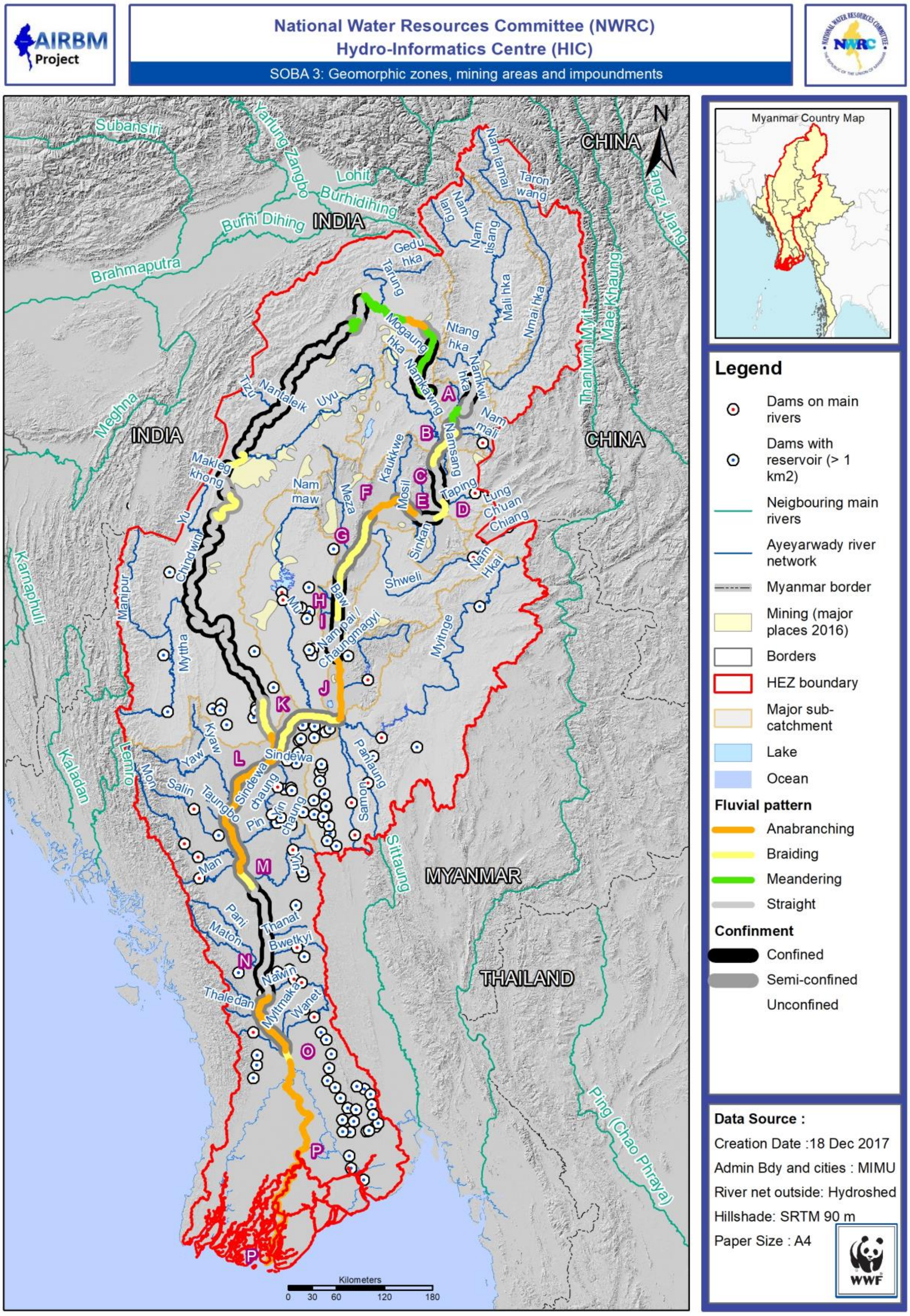


Figure 1.8 - Estimates of fine-grained sediment transport during the field expedition. *X-axis denotes geomorphic zones and specific stations along river.*

The geomorphic issues and risks identified by the results of SOBA 3 have been divided into three broad, overlapping categories:

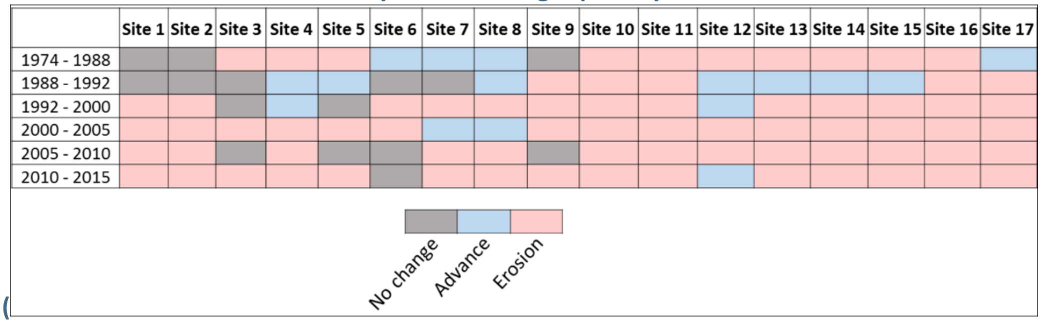
- **Bank and channel morphology and stability —** The physical attributes and condition of the banks and bed are important for maintaining the connectivity of the river channel, for supporting and protecting the infrastructure developed along the river (roads, bridges, irrigation pumps, shipping facilities) and critical for safe and efficient navigation. The maintenance of bank stability and channel capacity are also important for flood prevention and the maintenance of floodplains. The geomorphic zones most susceptible to change are the broad alluvial areas with low slope in which sediment deposition and reworking are constantly occurring, especially those downstream of higher slope and energy zones that can deliver large loads of sediment that cannot be easily mobilised through the wider, low-slope reaches. Indicators associated with monitoring and managing these issues include accurate flow and sediment measurements (including grain-size), repeat channel cross-sections, and land use changes (deforestation, mining, sand and gravel extraction, hydropower irrigation;



- Figure 1.9).
- **Sediment transport and river connectivity —** The second general area overlaps with the previous, but reflects a larger, basin-wide consideration of changes and connectivity. The continuous movement of material through the river controls the channel and bank characteristics, and nutrient dispersal and availability, which is relevant to biodiversity, fisheries, and the important economic

sectors of agriculture and construction. Nutrient transport is not a geomorphic process per se; however, the inextricable link between sediment and nutrients needs to be recognised and considered in basin planning. Monitoring the condition and sediment transport through the high-Strahler order river segments is required to understand processes such that development can be managed to maintain these important links. In addition to flow, sediment, and channel indicators, nutrients should be included as long-term indicators.

Delta stability — The final area of major geomorphic risk is associated with the maintenance of the Ayeyarwady Delta. River deltas are the culmination of all processes occurring in the upstream catchment, and an important interface between the terrestrial, fluvial, and marine environments. On a physical level, deltas are created and maintained by the delivery of sediment from a river to the coast, and maintaining sediment supply is critical for maintaining delta stability and to maintain the productivity of coastal areas. Deltas and resilient coastlines provide protection against floods and typhoons, host a wide range of ecological habitats, provide fertile land for agriculture and coastal areas for urban development and recreation. Recent investigations of the Ayeyarwady Delta conclude that the resilience of the delta may be decreasing especially near the mouths of the main distributaries (



- Figure 1.10).

Similar flow, sediment transport, land use, and channel change indicators are required to understand the linkages between the river system and the delta, but monitoring should include cross-sections and channel long-sections through the delta periodic assessment of changes to the delta front based on satellite imagery.

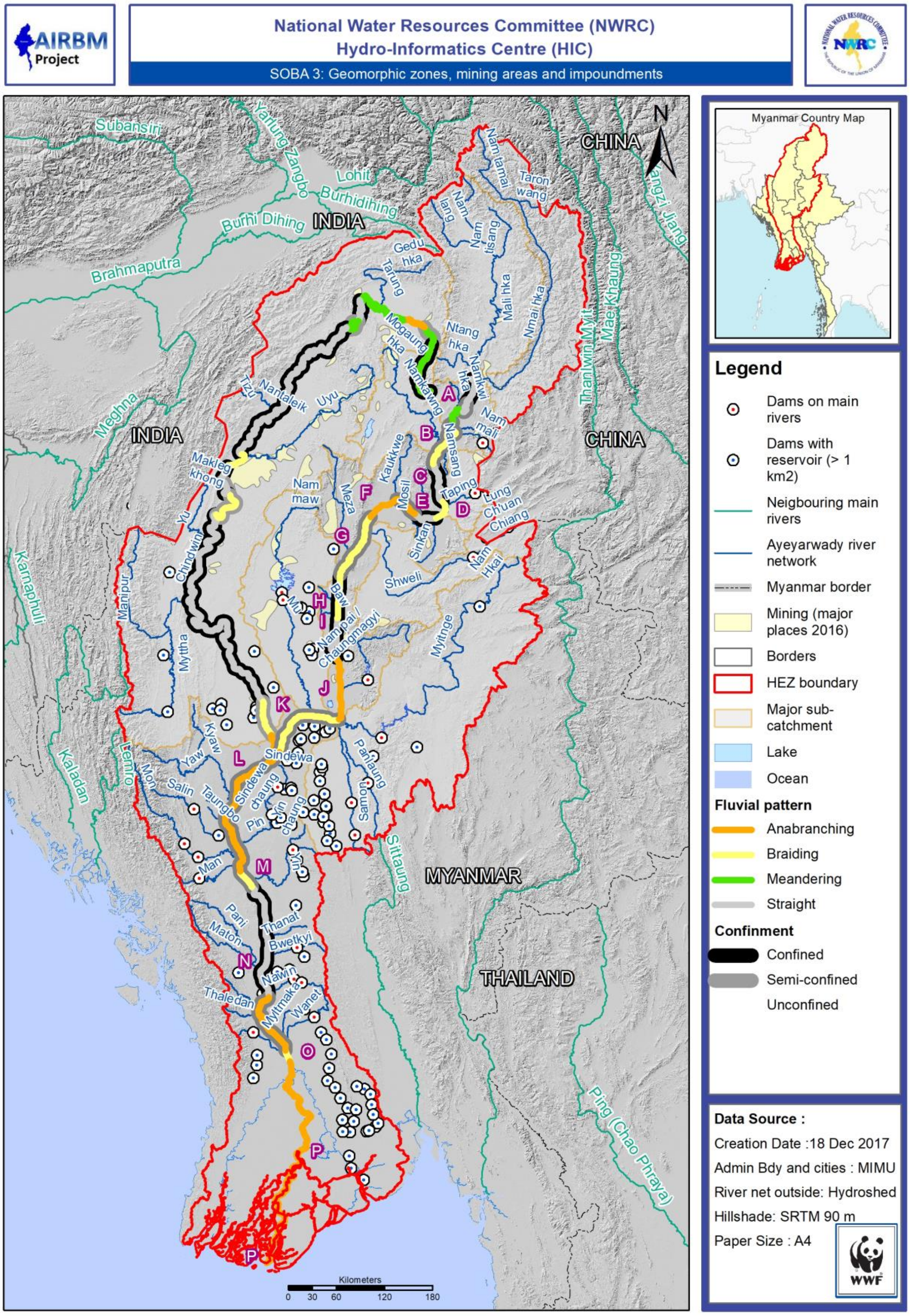


Figure 1.9 - Summary of land and river use pressures in the Ayeyarwady Catchment

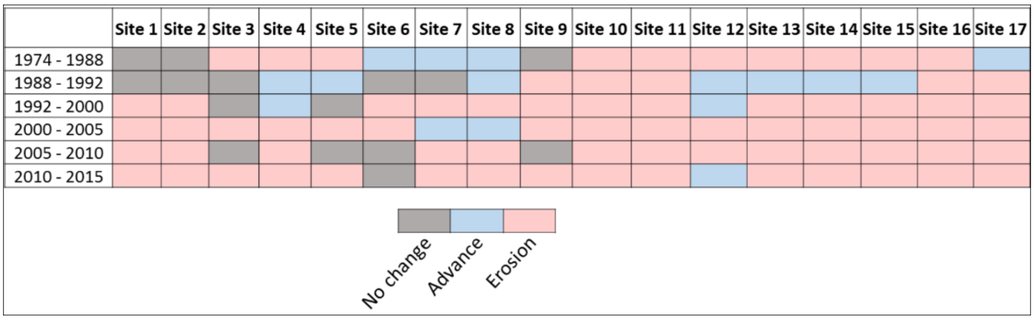


Figure 1.10 - Results of a vulnerability assessment of the delta showing trends in erosion and advance. ***Sites 10 through 17 are located at the mouths of the distributaries of the Ayeyarwady with the other sites located towards the east of the delta front. (Anthony et al., 2017a).***

Completing a trend analysis for parameters such as flow and sediment transport was not possible due to the questions regarding the accuracy of the available monitoring results. An analysis of water levels during the dry season suggests that flow changes consistent with regulation for hydropower and irrigation may be occurring, but the instability of the river cross-sections at the monitoring points makes these finding questionable. Trend analysis was completed on land and river use changes, which shows accelerating rates of land disturbance associated with deforestation and mining. These localised land use changes have a high likelihood of increasing sediment inputs at discrete points in the river. The trend analysis for hydropower found that the past level of hydropower development has been moderate, but the number and size of projects under development and projected over the next two decades reflects a very large increase in the potential river fragmentation and regulation of the river. Of particular note is the planned development of numerous 'mega' dams, with heights over 100 metres (m) and storage capacities in excess of 1 cubic kilometre (km^3). These projects have the potential to dramatically alter the flow of rivers and trap large volumes of sediment. The concentration of hydropower in the upper Ayeyarwady presents an additional risk, as this area provides the majority of flow in the river, so flow regulation will have basin-wide impacts. Less clear are trends in irrigation due to a lack of information, but the focus on economic growth and investment in Myanmar and the importance of agriculture to the economy suggest that regulation for irrigation is also likely to increase in the future. Finally, the present rate of sand and gravel extraction is likely near or beyond the bounds of sustainability, recognising the lack of a reliable sediment budget. The rate of sand and gravel extraction generally parallels construction trends due to the dependence of the construction industry on this commodity. The projected increased investment and growth in Myanmar into the future will likely translate into an increase in the demand for sand and gravel, placing an additional stress on the river.

The findings of the investigations and trend analysis highlight the need for improved monitoring, and an approach for a sediment monitoring system is presented as a starting point for discussion. The proposed monitoring is integrated with discharge monitoring and an initial two-year development period is suggested, during which time physical samples will be collected. The information will provide an immediate snap shot of sediment transport in the river and sediment characteristics, and the basis for the calibration of other remote sensing techniques such that physical monitoring can be reduced in the future. Data management and capacity building are important components of the strategy. Sediment monitoring is proposed to be completed as part of a larger monitoring strategy to fill the identified data gaps. Monitoring and information gathering is recommended to include: repeat channel cross-sections in the river and delta, land use analysis based on satellite imagery, and the development of databases relating to hydropower, irrigation, forestry, and mining to track trends in these activities.

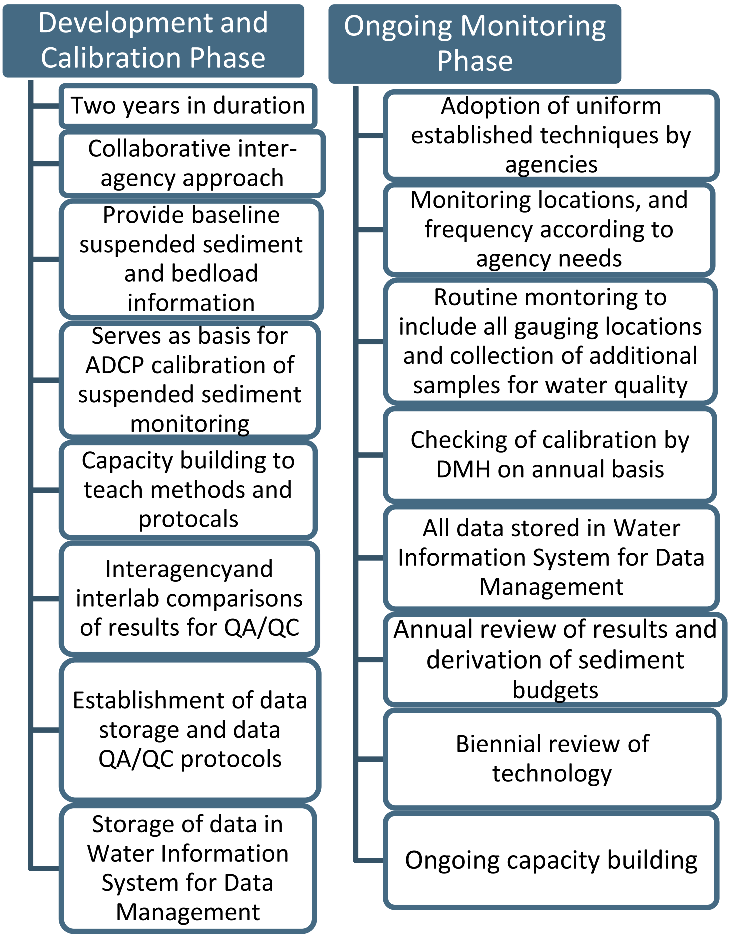


Figure 1.11 - Summary of proposed two-phased monitoring program

The overall finding of the SOBA 3 Report is that the geomorphology of the Ayeyarwady River is in moderate to good condition, owing to the lack of regulation of the main stem, and the flow and sediment inputs from the remaining unregulated tributaries. The pressures on the river, however, are mounting at a rapid pace, and accelerating land use changes will impact the river at increased rates and severity if the linkages between land and river are not recognised and more appropriately managed.

Recognising, understanding, and managing these land-river relationships is the first step towards sustainable development. For example, the navigation issues widely recorded downstream of Mandalay are likely linked to land use activities and regulation of tributaries as far upstream as Katha. Implementing land use policies that control runoff from mining and forest operations, and require hydropower plants to provide appropriate flows for the maintenance of geomorphic processes, are the best first steps towards sustainable use of the resources of the Ayeyarwady. Sustainable development can only be based on accurate and up-to-date information about the river and its flow, sediment transport, and channel characteristics. Implementing sediment and geomorphic monitoring, and interpreting the results in the context of the catchment, delta and land uses is the primary recommendation from the SOBA 3 Team.

1. INTRODUCTION

The Ayeyarwady Integrated River Basin Management (AIRBM) project is developing a State of the Basin Assessment (SOBA) Report for the Ayeyarwady River. The aim of AIRBM is to provide Myanmar with relevant and accurate information for use in implementing integrated basin management in the Ayeyarwady. The SOBA component of the project is to provide an accurate and up-to-date baseline of the catchment capturing the existing conditions and historic trends of the key characteristics of the river basin, and how the people of Myanmar use and benefit from the resources of the river. The State of the Basin Assessment 3: Sediments and Geomorphology (SOBA 3) is focused on the Sediments and Geomorphology of the Ayeyarwady, and includes the following aims:

- Assess the status and trends of key characteristics of the basin's geomorphology and sediment dynamics;
- Analyse these trends to assess their implications for the Ayeyarwady system; and
- Recommend a conceptual design for a sediment and geomorphic monitoring program on the Ayeyarwady River.

Geomorphology and sediment transport is a complex and far reaching topic, due to the large range of spatial and temporal scales over which river processes operate. Rivers integrate and respond to changes in geological, hydrological, land use, and river use conditions. These changes may be sudden and short-term, such as the large influxes of sediment or rapid channel changes associated with an extreme flood event, or may occur over decades to centuries, such as the response to progressive land use changes, tectonic or geologic forces, or climate change. Spatially, changes also occur over a range of scales, with local river alteration potentially resulting in changes far removed. An example is the regulation of flow in a large tributary that alters the local flow balance between the Ayeyarwady and the tributary, leading to geomorphic changes both upstream and downstream of the river's confluence. In large rivers such as the Ayeyarwady, the progressive changes to land use or river use, such as damming or channelization, may induce little response in the river until thresholds are reached, beyond which change is rapid and irreversible. Identifying the relationships and linkages between processes operating over different time-frames is difficult and requires an understanding of the catchment, rather than just the river channel that is integrating and responding to these changes.

The SOBA 3 Team approach has been to identify, describe, and quantify, where possible, the processes occurring within the main stem of the Ayeyarwady, and link these processes back to land- and river-based activities contributing to and controlling these conditions. As in any large river system, the Ayeyarwady is highly variable, and is responding to multiple pressures simultaneously. Teasing out the major drivers and establishing key linkages requires accurate information about the hydrology and sediment transport of the river, and the land-based activities affecting change in the system.

SOBA 3 has adopted a range of approaches and techniques to identify and explore the important geomorphic and sediment transport processes operating in the Ayeyarwady. These include a review of relevant literature, extensive analysis of satellite imagery to understand land and river changes over the past few decades, field-based investigations and sampling to document river characteristics at a local scale, analysis of sediment samples and interpretation of results with respect to local sediment transport processes and catchment wide trends, and industry-based surveys to elucidate the present status of sand and gravel extraction in the river. The results provide an up-to-date and informative picture of the status of the river catchment with respect to geomorphology and sediment transport.

In every investigation, there are limitations, and the SOBA 3 project is no exception. The work has been somewhat limited by the following factors:

- The short duration of the project (<6 months) limited the ability to observe, sample, and document processes or activities over a full hydrologic year. In particular, the study period (May to September) did not include the dry season, so field observations of the full extent of riverbanks and bars were not possible due to elevated water levels. The SOBA 3 Team attempted to limit the impact of this constraint by conducting field investigations prior to the commencement of the project, but water levels were already increasing when field work commenced in April.

- The short duration of the project, combined with the elevated water levels, limited field work to the Ayeyarwady River upstream of the delta only. The SOBA 3 Team recognises the importance of the delta, Chindwin and other large tributaries to the overall functioning of the Ayeyarwady system, but field work was not feasible beyond the main river channel due to the onset of the flood season. The interpretation of satellite imagery has provided insights into the characteristics of the Chindwin and other major tributaries, and close consultation with other World Wildlife Fund (WWF) projects investigating the Ayeyarwady Delta have provided information about the delta to help extend the understanding of this critical area of the catchment.
- Access to a 245 km reach of the Ayeyarwady was limited due to security issues. This reach extends from downstream of Myitkyina to approximately 15 km upstream of Bhamo. The local characteristics of this area were not able to be observed and no sediment samples were collected from this reach, which is an important transitional area between the headwaters of the river and the lower river. It also hosts considerable mining activities that can affect the geomorphology of the river locally and downstream.
- The availability and quality existing information. There is limited sediment transport and geomorphic information available for the river. Long historical records exist, but the results have been found to be unsuitable for analysis due to a variety of factors. This has prevented the derivation of sediment budgets based on existing information, but the SOBA 3 Project has identified important areas of sediment input and provided indicative proportions of input from these areas as a basis for discussion, future investigations and derivation of accurate sediment budgets.

The structure of this report is as follows:

- Section 2 provides an overview of the catchment and the river, starting with the large-scale geologic, tectonic and hydrologic processes that govern the geomorphology of Myanmar and the Ayeyarwady. This information is used to identify geomorphic zones along the river and present a description of the large-scale characteristics of the Ayeyarwady by geomorphic zone.
- Section 3 focuses on catchment activities that have direct linkages to the geomorphic functioning of the river, including land use changes (deforestation and mining) and river use changes (hydropower, irrigation and sediment mining). This information is based on available literature, extensive analysis of satellite imagery to capture the evolution of changes, and field-based surveys to quantify sand and gravel extraction from the river.
- Sediment transport and sediment characteristics are described in Section 4, including the results from over 300 sediment samples collected as part of the field investigations. This information is used to document large-scale trends in sediment grain-size over the length of the river, and to elucidate the flow conditions at the time of transport and deposition, thus providing insights into how sediment is moved through the system. The culmination of this section is the derivation of a hypothetical sediment budget, for both fine-grained and coarse-grained sediment, that fits the sediment transport and geomorphic information and observations.
- Issues associated with geomorphology in the Ayeyarwady are identified in Section 5, and relevant indicators are proposed for the long-term monitoring and tracking of these issues. Where sufficient information is available, a trend analysis based on historic and potential future changes is completed for each indicator. Information gaps associated with the indicators are highlighted in the discussion.
- Section 6 draws together the identified data gaps from the SOBA 3 findings and proposes a way forward with respect to sediment monitoring. The findings of SOBA 3 highlight the need for the immediate implementation of sediment monitoring to provide up-to-date and accurate sediment transport information.

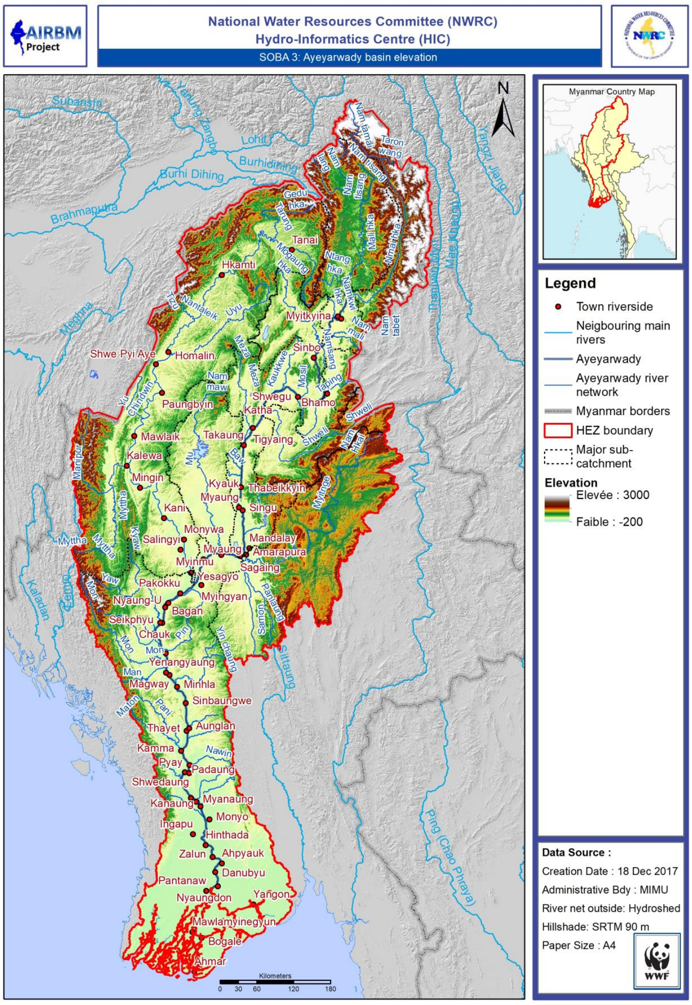
- Sediment monitoring needs to be integrated into a larger hydrologic and landscape monitoring regime; information gaps related to these other geomorphic topics are discussed in Section 7, along with recommendations.

2. AYEYARWADY SETTING

The natural geomorphic characteristics of the Ayeyarwady River are the result of the interaction between the underlying geology and tectonics of the region, and the catchment rainfall and land use. This chapter provides an overview of the characteristics of the Ayeyarwady River basin, the underlying tectonics and geologic attributes, and a short summary of the rainfall characteristics contributing to landscape development. Based on these attributes, geomorphic zones are identified and described.

2.1 Overview of Catchment

The Ayeyarwady River basin has an area of approximately 414,000 km^2 and occupies ~60% of Myanmar, extending ~1,400 km from the northern national boundary to the Andaman Sea. In the northern half of the catchment, the river occupies two generally north-south trending parallel valleys, bounded by the Rakhine mountain ranges in the west and the Shan Plateau in the east. Relatively low north-south trending hills separate the two valleys (



National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Ayeyarwady basin elevation
Myanmar Country Map
Legend
Town riverside
Neigbouring main rivers
Ayeyarwady
Ayeyarwady river network
Myanmar borders
HEZ boundary
Major sub-catchment
Elevation
Elevée : 3000
Faible : -200
Data Source :
Creation Date : 18 Dec 2017
Administrative Bdy : MIMU
River net outside: Hydroshed
Hillshade: SRTM 90 m
Paper Size : A4
Kilometers
0 30 60 120 180
Hkamti
Myitkyina
Homalin
Bhamo
Katha
Mandalay
Sagaing
Monywa
Pakokku
Bagan
Magway
Pyay
Hinthada
Yangon
Bogale

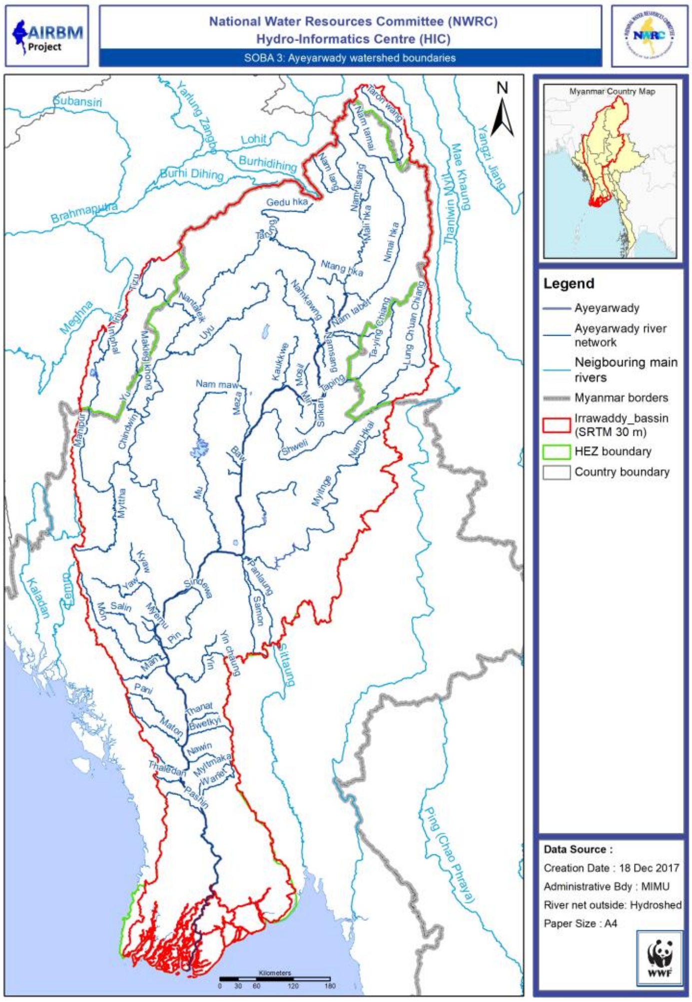


Figure 2.1).

The broad, flat western valley is occupied by the largest tributary, the Chindwin River, while the narrower, but longer eastern valley holds the Ayeyarwady main stem. The Chindwin is predominantly fed by eastward flowing tributaries arising in the Rakhine mountain ranges, while the tributaries of the upper Ayeyarwady predominantly drain the elevated Shan plateau and flow from east to west. The Mu tributary is the largest waterway draining the central region dividing these two large rivers.

The two major headwater tributaries of the Ayeyarwady, the N'mai Hka and Mali Hka, have their source in the high glacial mountains of northern Myanmar where elevations exceed 5,000 m and glacial snowmelt provides an important water input during the dry season. The confluence of these two large rivers is arbitrarily considered the start of the Ayeyarwady.

Downstream of the confluence of the Chindwin and upper Ayeyarwady Rivers, the river flows southerly through low hills before emerging onto alluvial areas grading into the large delta. The Ayeyarwady downstream of the Chindwin confluence is fed by tributaries draining the southern hills of the Southern Rakhine Mountains in the Rakhine Yoma (local name for mountains) range from the west, and the Bago Yoma range in the east.

The Ayeyarwady and Chindwin main stems lie completely within Myanmar, however the basin extends beyond the national boundaries with approximately 9% of the catchment area located outside of Myanmar. At the direction of the SOBA PMU, the maps in this report show the national boundary of Myanmar as the limit of the Ayeyarwady River basin and the Hydro Ecological Zones (HEZs). Figure 1.1 compares the national border and the natural catchment boundaries and shows transboundary tributaries in the north, west and east of the catchment. Table 1 lists the areas of transboundary tributaries and the percentage of each located within Myanmar.

Catchment areas beyond the national boundaries have been included in all geomorphic analyses completed for this investigation. From a geomorphic perspective these areas are important to consider as they receive high levels of rainfall and would naturally provide high levels of sediment and flow to the Ayeyarwady. Developments within these transboundary basins will directly impact the geomorphology of the Ayeyarwady and contribute to cumulative impacts on a regional and basin scale. An example is the intensive hydropower development in the Shweli River in China that has altered the sediment input and flow regime of the river as discussed in Section 2.9 in the Sinuosity and Braiding Analysis.

Table 1. Transboundary tributaries in the Ayeyarwady River catchment

Tributary	Area of catchment Km^2	Percent of catchment within Myanmar
N'Mai Hka	24,361	82.4
Shweli	23,022	57.9
Taping	10,023	37.9
Nam Tabet	1,664	40.3
Chindwin	114,169	85.0

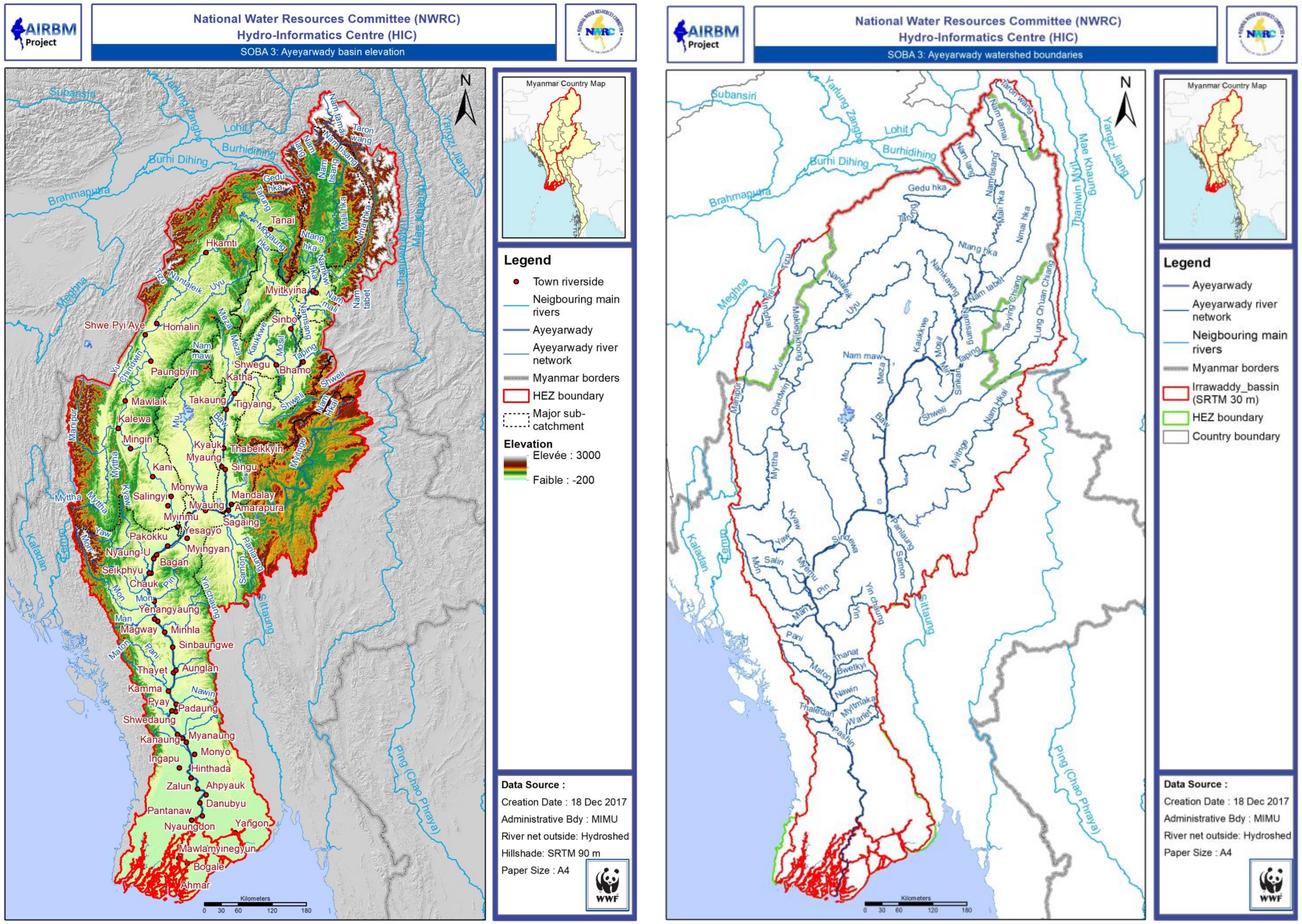
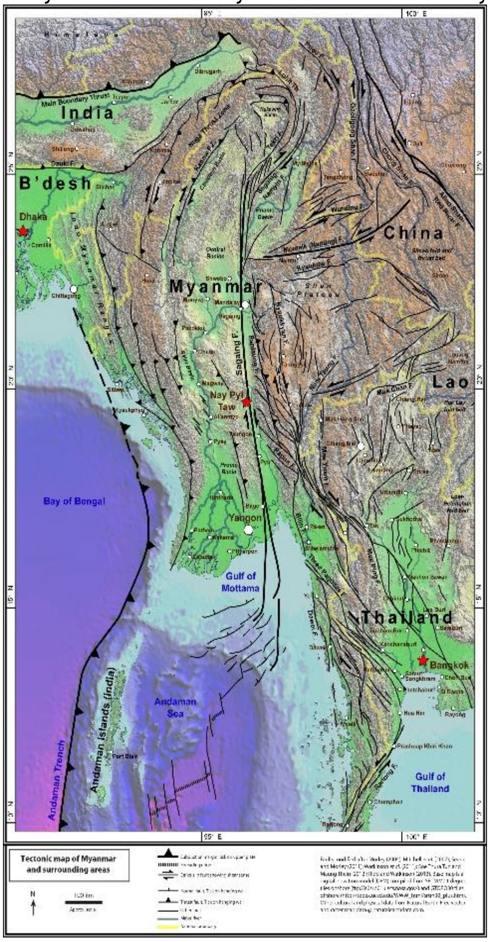


Figure 2.1 (left) Map of the Ayeyarwady River Basin showing elevation and major tributaries, (right) catchment area beyond national boundaries.

2.2 Tectonic and Geologic Setting

The geomorphic characteristics of the Ayeyarwady River are closely linked to the underlying tectonics and geology, as shown in the maps of Figure 2.2 and



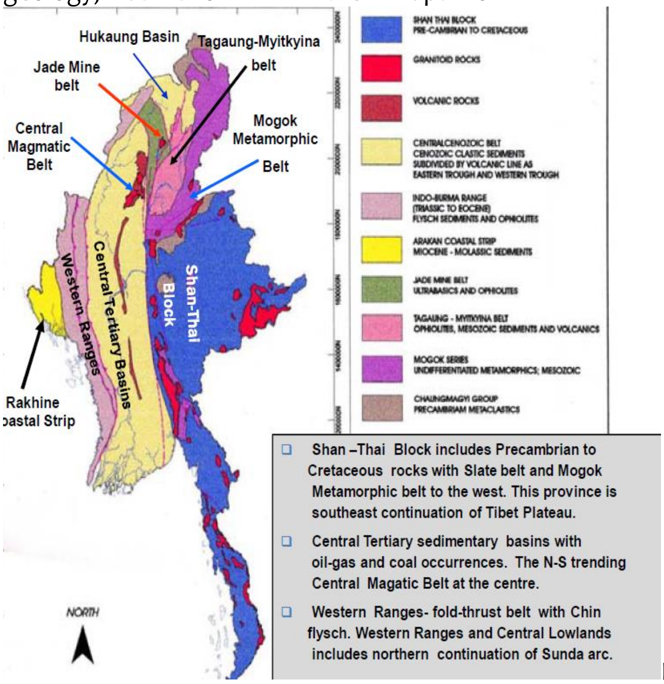


Figure 2.3. For more detailed tectonic and geologic maps, refer to Annex 1, which contains maps from the Myanmar Geosciences Society. Wang *et al.*, (2014) provide a detailed overview of how the tectonics of Myanmar are expressed through landscape attributes. Myanmar has a very active tectonic setting, as the country occupies the collision zone between the Indian and Eurasian Plates. This collision zone is delineated by the north-south trending Sagaing fault

which roughly cuts Myanmar in half. On the western side, the Indian plate is moving northward, whilst on the eastern side the Eurasian Plate is moving southward, with additional east-west movement along ancillary faults to accommodate plate movements (Wang *et al.,* 2014). The active subduction and thrust faulting occurring along western Myanmar increases the complexity of the setting, as it is responsible for the relatively young north-west trending parallel thrust faults in the Arakan mountain range. East of the Sagaing fault, the geology of Myanmar is characterised by older, more crystalline strata that form the elevated Shan Plateau, and the northern sediment, metamorphic, and volcanic belts that reflect the southern extent of the Tibetan Plateau (Swe, 2013).

These tectonic and geologic characteristics exert a strong influence on the landscape of Myanmar with the headwaters and tributaries of the Ayeyarwady draining steeply sloping areas, but the main channel predominantly occupies broad low-slope basins developed on softer strata (

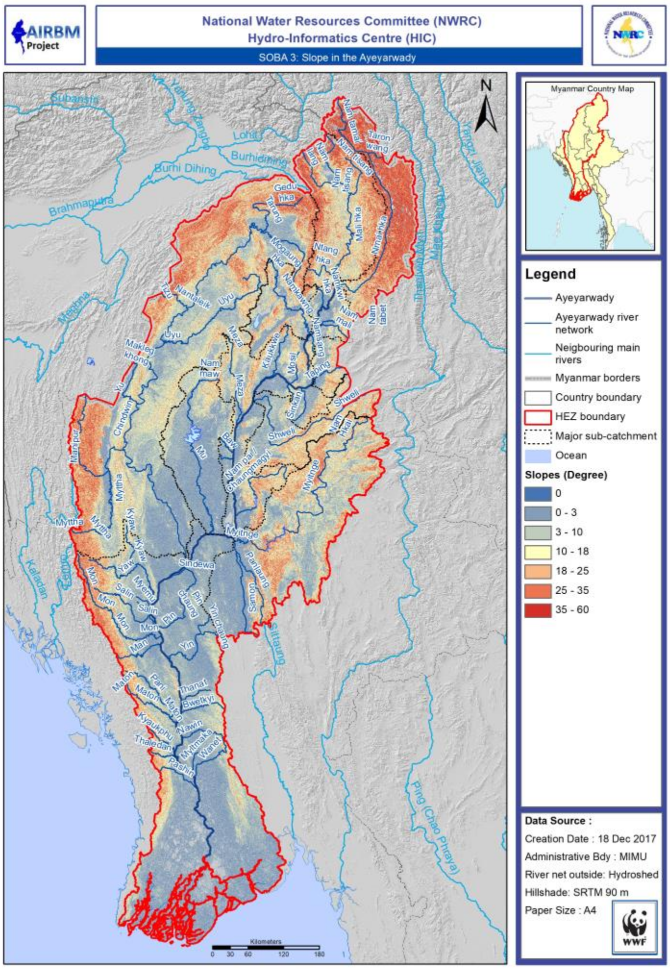


Figure 2.4). The ‘defiles’ (narrow passes or gorges) of the Ayeyarwady are associated with the river cutting through the more resilient units. In the upper Ayeyarwady, the river occupies the shear zone for a length of approximately 100 km, between km 900 and km 1,000 on the SOBA 3 catchment maps.

The tectonics and geology also exert a strong control on sediment generation. Headwater areas with steep slopes and high uplift rates would be expected to have higher weathering rates as compared to more quiescent areas of the catchment. The potential quantity and quality of sediment generated and transported in the river basins is also linked to the geologic setting of the Ayeyarwady. Flysch deposits, such as those in the Arakan Mountains to the west, tend to erode quickly and produce abundant silts, muds, and sands due to the presence of mudstones and high susceptibility to weathering. Stamp (1940) noted that the soft strata in the Chindwin was easily eroded by pitting erosion associated with the impact of clasts against the soft banks. In contrast, the harder more crystalline Shan Plateau and eastern mountain ranges are likely to be more resistant to physical weathering, and produce higher proportions of sands and resilient gravels as compared to silts or clays.

The complex faulting has contributed to the development of numerous broad basins within the Ayeyarwady catchment, with the largest, the Central Basin, located between the Arakan mountains and the Sagaing fault zone. The basin is occupied by the Chindwin and Mu Rivers with the Ayeyarwady flowing along the southern boundary between Mandalay and the Chindwin confluence. Smaller basins occur within the upper Ayeyarwady, between the Sagaing fault zone and the western edge of the Shan Plateau between Myitkyina and where the river enters the Sagaing fault zone at Tagaung. Faulting associated with the northern extent of the Sagaing zone is also responsible for the basin hosting Lake Indawgyi, one of the largest fresh water lakes in Asia. These basins are areas of sediment deposition and reworking and are important from a fluvial geomorphological perspective as they are sensitive to changes in hydrology and sediment supply.

The relationship between tectonics, geology and geomorphology is discussed in more detail in Section 2.5.

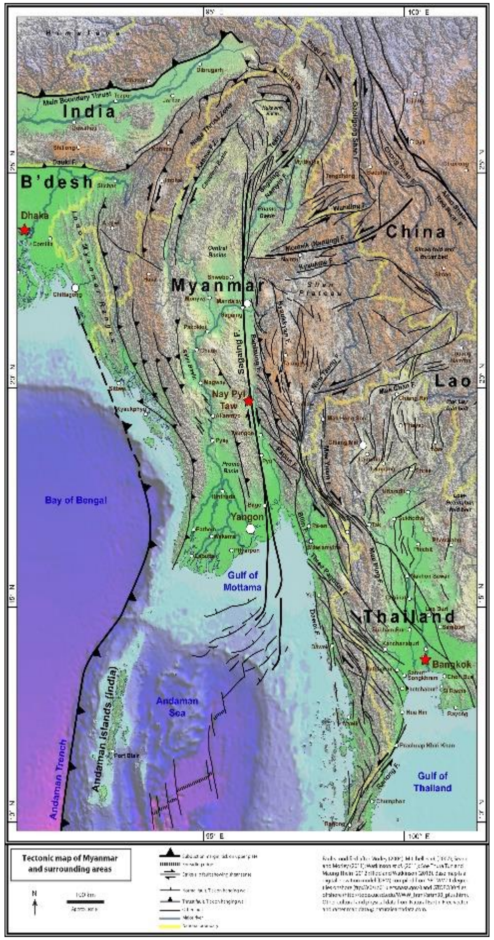


Figure 2.2 - Tectonic setting of Myanmar

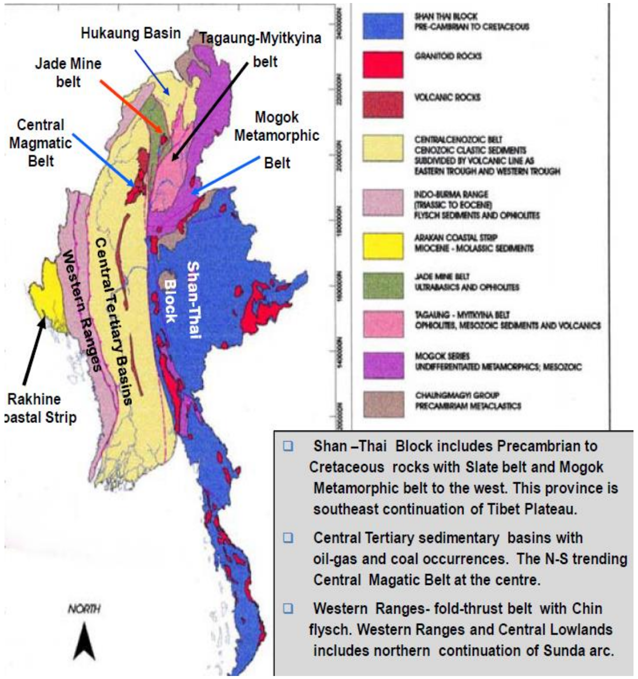


Figure 2.3 - Simplified geology of Myanmar

(Ye Mint Swe, 2013)

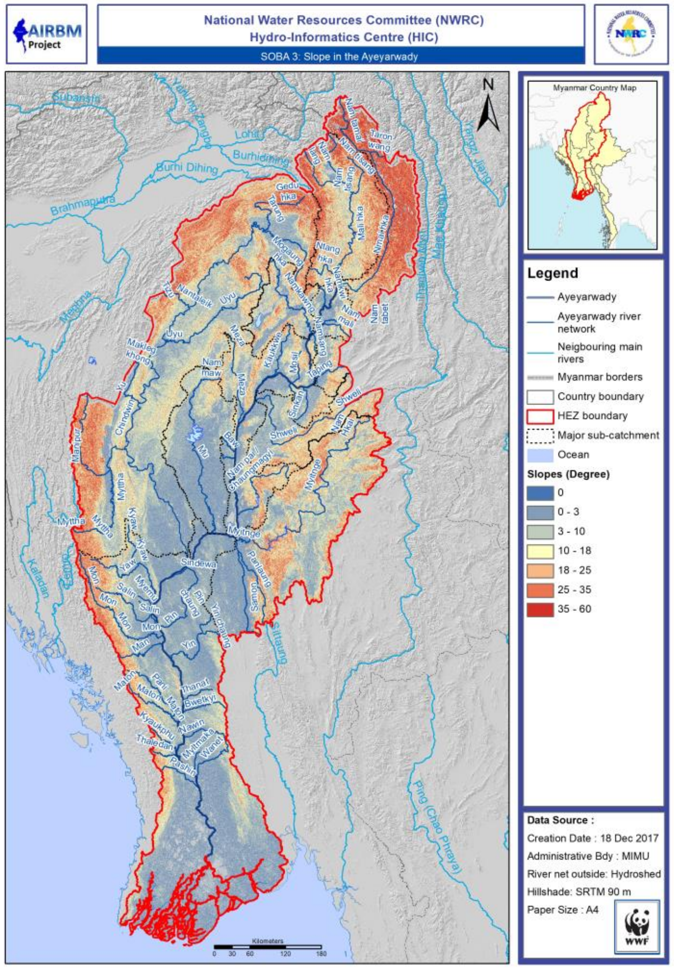


Figure 2.4 - Slope classes in Myanmar
(Shuttle Radar Topography Mission [SRTM] - Digital Elevation Model)

2.3 Hydrology

Other components of the SOBA provide in-depth reviews and analysis of the hydrology of the Ayeyarwady. This short section is limited to highlighting some of the most important hydrologic features of the catchment with respect to understanding the geomorphology of the river. These attributes include:

1. The monsoonal seasonality of flow in the Ayeyarwady;
2. Variable rainfall patterns, with higher rainfall totals in the north and south as compared to the Central Dry Zone; and
3. Flow regulation associated with hydropower and irrigation dams.

Each of these is briefly discussed in the following sections.

2.3.1 Seasonal rainfall and river discharge patterns

Rainfall patterns and totals in Myanmar are governed by the southwest monsoon and the physiography of the country. Average annual rainfall is shown in

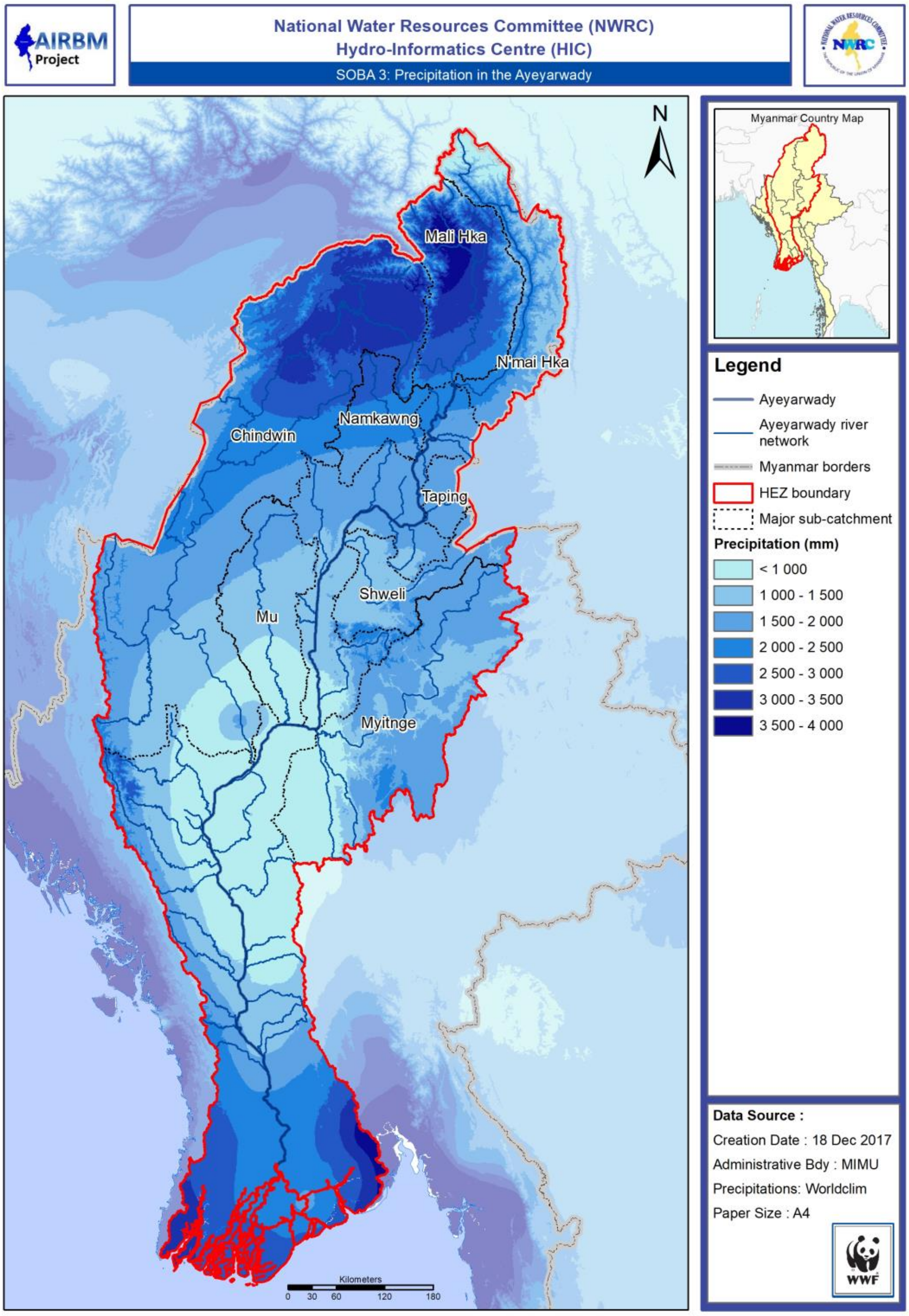
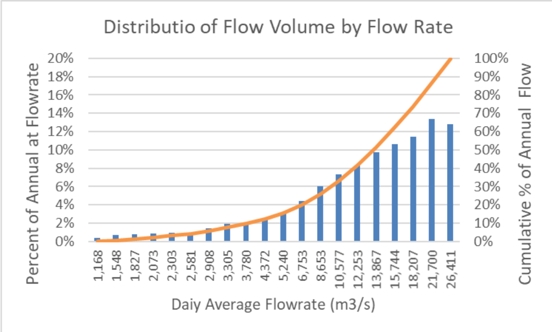


Figure 2.5. Over 90% of rainfall in Myanmar occurs during the May to October monsoon season, with the Central Dry Zone located in the rain shadow of the Western Ranges (Furuichi *et al.,* 2009). Rainfall totals increase in both directions from this central dry area.

The pattern of the monsoon dictates the rise and fall of the Ayeyarwady, with maximum river levels occurring from July to September. The average annual discharge in the Ayeyarwady was estimated at 440±48 x 10^9 cubic metres (m^3) by Robinson *et al.,* (2007) which is widely cited in the literature. Based on monthly records at Pyay from 1966 to 1996, Furuichi *et al.,* (2009) found that average monthly flows in the lower river ranged over an order of magnitude, from 6.3 x 10^9 m^3 in February to 79.25 x 10^9 m^3 in August. Within this range, the



distribution of flows is not uniform, as shown in Figure 2.7, where the total annual flow volume is compared to the proportion of the total flow that is delivered at different daily flow rates. The daily flow rates (x-axis) correspond to the 1st, 5th, 10th, 15th, etc. flow rates based on an analysis of 44 years of daily flow data from the Sagaing gauging station. The graph shows that less than 15% of the total annual flow is delivered at flow rates of 4,372 m^3s^{-1}, which is the median daily flow rate, with flow rates up to 10,577 m^3s^{-1} (the 70th percentile daily flow rate) cumulatively delivering only ~35% of the annual flow. Continuing this analysis shows that approximately 50% of the annual flow volume is delivered by the top 20% of flows (daily flow rates >13,867 m^3s^{-1}). Recognising these hydrologic patterns is important for sediment transport, as the channel form and coarse-grained sediment movement in the Ayeyarwady will be determined by these relatively short-duration, peak flow events, with the movement and deposition of finer material occurring during interceding long periods of low flow.

The rate of water level change is another component of the flow regime that is important for geomorphology and sediment transport. Rapidly rising water levels increase shear stress due to increased water surface slopes and promote erosion through scour. Rapidly decreasing water levels can cause seepage erosion of banks as saturated banks become unstable when water levels recede. An analysis of 20-years of daily water level fluctuations at Sagaing in the middle Ayeyarwady (

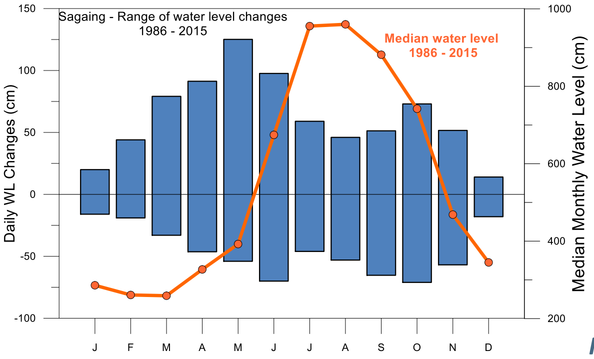


Figure 2.8) and Pyay in the lower Ayeyarwady (

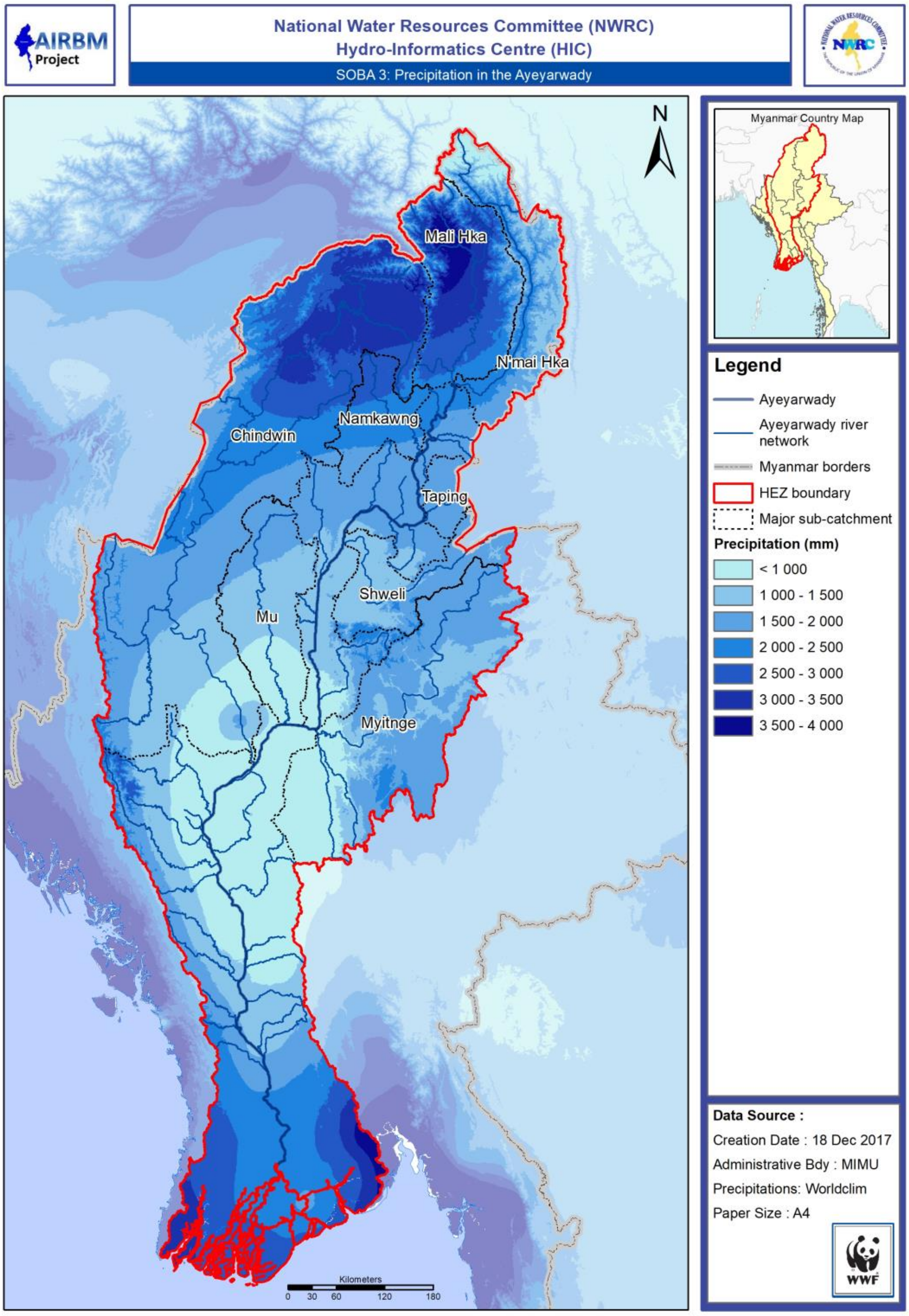


Figure 2.5) shows that there are similar trends at the two sites linked to the seasonality of the monsoon.

Water level fluctuations are lowest during the dry months of December and January. Large increases in daily water level fluctuations are registered in March to June, with May recording the highest rates of increases at both sites. These rapid increases and lower decreases are attributable to the episodic rainfall that is associated with the early stages of the monsoon. Rates of increase exceed rates of decrease due to the slower recession rates, as compared to rising rates of storm events, and due to the gradual increase in sustained flow levels. During this rising limb of the monsoon, high rates of scour can mobilise finer material deposited during the previous dry season and large volumes of sediment, contributing to an initial sediment pulse.

During July and August, when the river levels peak, water level fluctuations are reduced. This is attributable to constant inflows, and channels at or near capacity. At these river levels, increases in river flow do not translate into large water level changes, as floodplains are likely becoming accessible. In August, the monsoon begins to wane, resulting in higher rates of daily water level decrease, as compared to the increase that persists through November and December. Riverbanks are especially prone to seepage erosion during the recession of the monsoon, as they become saturated following inundation, and have a high risk of collapse as the water levels recede.

The similarity of the flow pattern between the middle Ayeyarwady and lower Ayeyarwady is attributable to the middle Ayeyarwady flow accounting for about half of the flow at Pyay, while the majority of the remaining flow is derived from the Chindwin, as discussed in the next section.

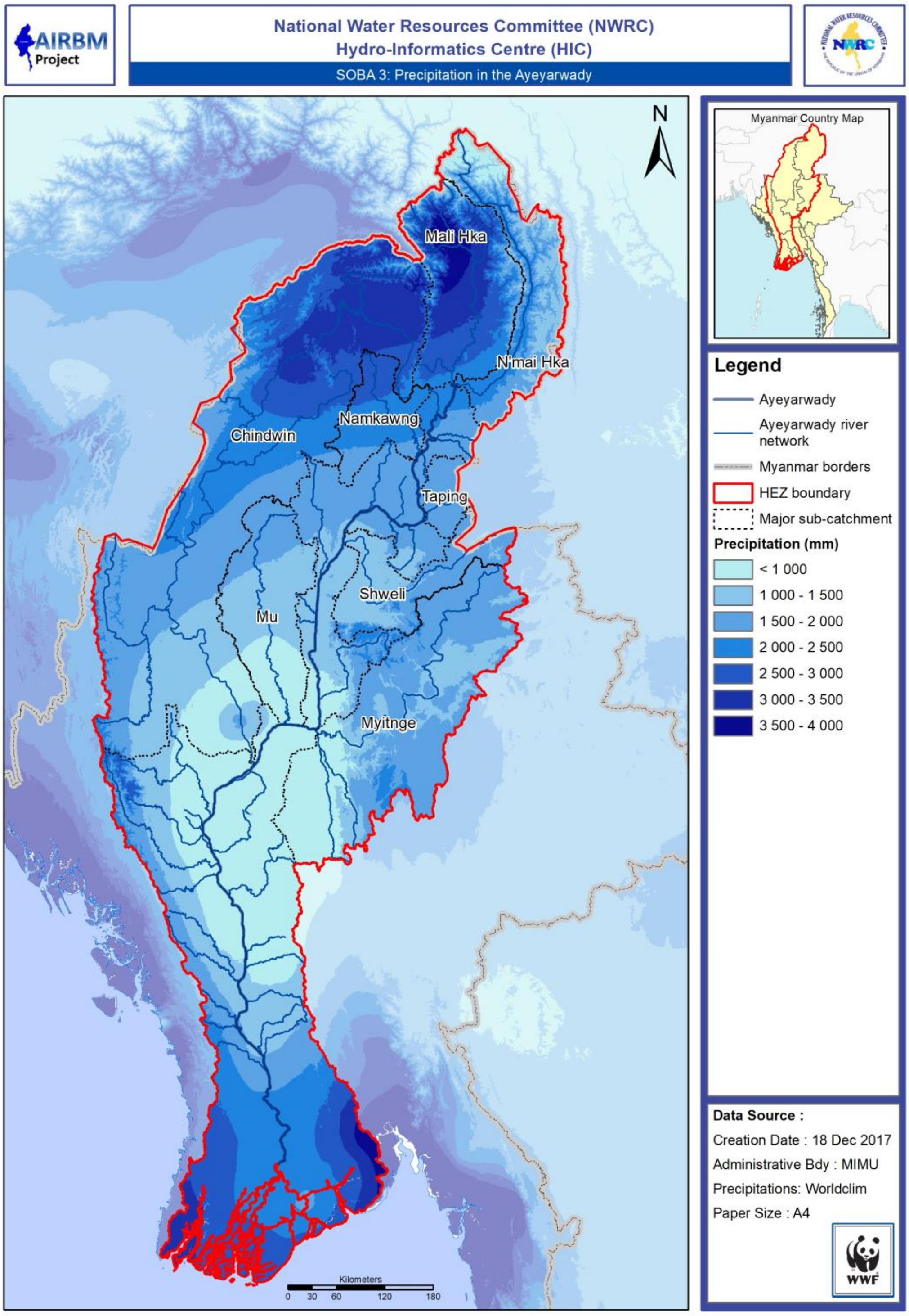


Figure 2.5 - Average annual rainfall in Myanmar (WorldClim)

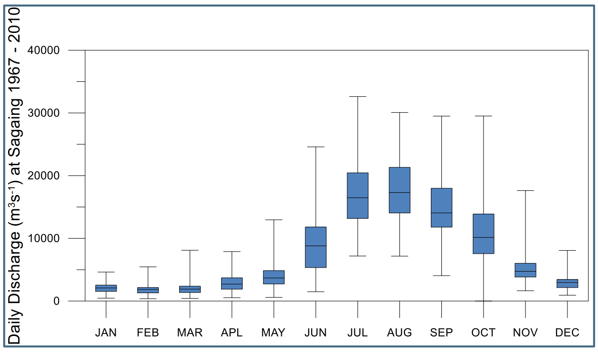


Figure 2.6 - Box and whisker plots of the range of daily discharge by month at Sagaing
Box Encompasses the 25th to 75th percentile values, with whiskers extending to minimum and maximum values (Department of Meteorology and Hydrology [DMH]).

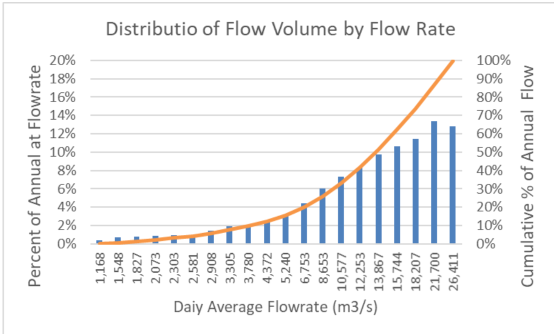


Figure 2.7 - Distribution of annual flow volume by daily flow rate at Sagaing (DMH)

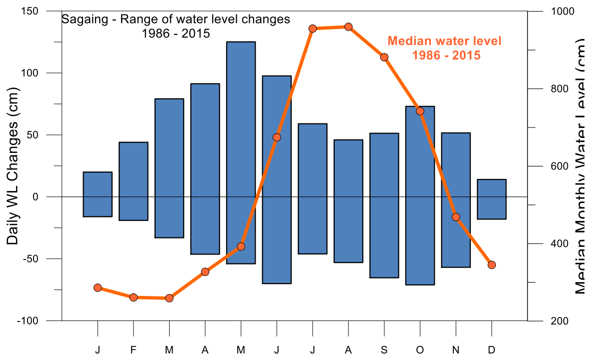


Figure 2.8 - Range of daily water level fluctuations at Sagaing in 1986 to 2015
Graph shows range between 1st percentile and 99th percentile water level changes based on daily water level measurements (DMH).

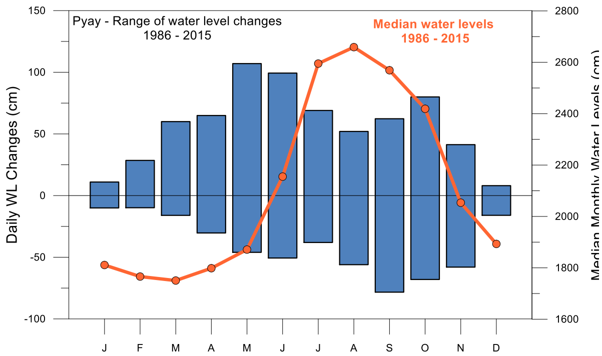


Figure 2.9 - Range of daily water level fluctuations at Pyay in 1986 to 2015
Graph shows range between 1st percentile and 99th percentile water level changes based on daily water level measurements (DMH).

2.3.2 Rainfall distribution

The variability of rainfall over the Ayeyarwady catchment (

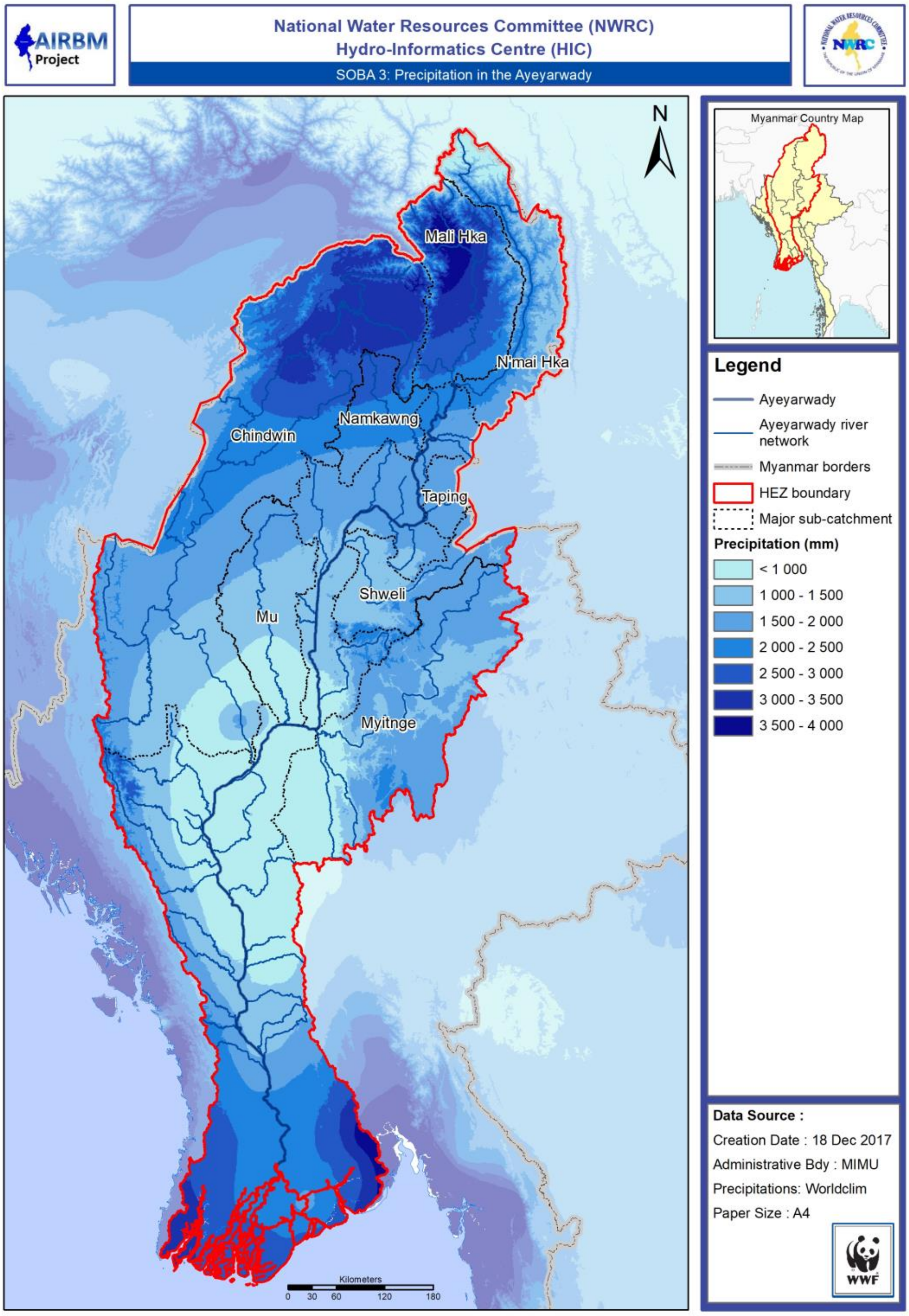


Figure 2.5) will affect the delivery of sediments into the main channel, and the transport of material through the river. The annual inflow volume from various areas of the Ayeyarwady catchment are shown in

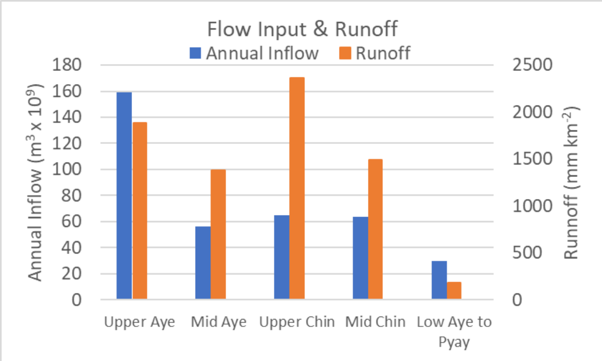


Figure 2.10, along with the runoff computed as millimetre (mm) per unit area derived from each of the sub-catchment areas. The upper Ayeyarwady (from the headwaters to Katha) provides the largest flow volume, accounting for about 40% of the total flow in the river from approximately ~25% of the total catchment area. The second largest flow contribution is derived from the upper Chindwin, where runoff per unit area exceeds that of the upper Ayeyarwady. The middle Ayeyarwady (from Katha to Sagaing) and middle Chindwin (from Hkmati to Mawlaik) are similar to the upper Chindwin with respect to total flow input, but the runoff rates are lower in these lower altitude, more southern regions of the river system.

The smallest input and the lowest rates of runoff are found in the lower Ayeyarwady, which encompasses the area downstream of Mawlaik and Sagaing covering about 167,000 km^2, equivalent to ~45% of the total Ayeyarwady catchment area. This region includes the Central Dry Zone (or Belt), that receives very low rainfall compared to the northern catchment or southern delta, which are not included in this analysis. In the Central Dry Zone, tributaries are ephemeral, and water and sediment input are likely episodic and related to rainfall intensity as well as rainfall totals, though no rainfall intensity data is available. The low runoff and low-flow volumes derived from the area highlight the dependence of the hydrology in the lower catchment on the magnitude and timing of inflows from the upper catchment.

Flow volumes are not available for gauging sites downstream of Pyay, but as rainfall increases towards the south, flow would also increase. Furuichi et al., (2009) estimate the catchment area downstream of Pyay at ~5,500 km^2. Estimates of the additional flow volume derived from this area range from ~28 x 10^9 m^3, measured by Gordon (1885) to ~65 x 10^9 m^3 estimated by Robinson *et al.*, (2007), based on a re-interpretation of Gordon's original data. These values result in very high runoff rates (>5,000 mm) which are similar to or exceed the annual rainfall for the area. The lack of balance of these values is not important; what is relevant is there is an extra pulse of water that enters the Ayeyarwady system near the head of the delta. This increase in flow may be locally important for geomorphic processes, but does not alter the overall shape of the hydrograph, as demonstrated by a comparison of water levels at Pyay, at the downstream extent of the dry zone and at Hinthada, within the delta (

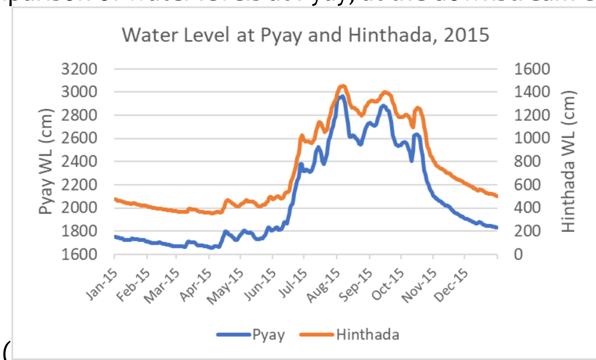


Figure 2.11).

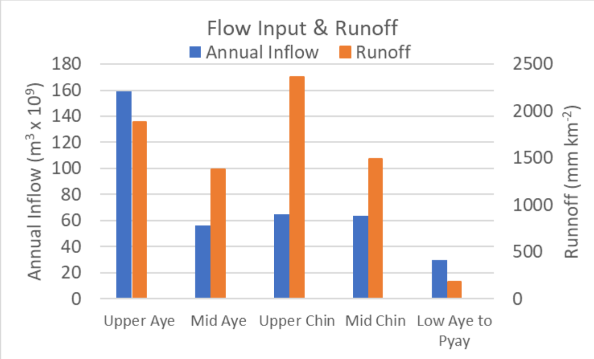


Figure 2.10 - Flow input and runoff from different areas of the Ayeyarwady
Upper Ayeyarwady = area upstream of Katha; Middle Ayeyarwady = area between Katha and Sagaing; Upper Chindwin = area upstream of Hkmati; Middle Chindwin = area between Hkmati and Mawlaik; Lower Ayeyarwady = area downstream of Sagaing and Mawlaik to Pyay (Rocha and Wilkinson, 2017).

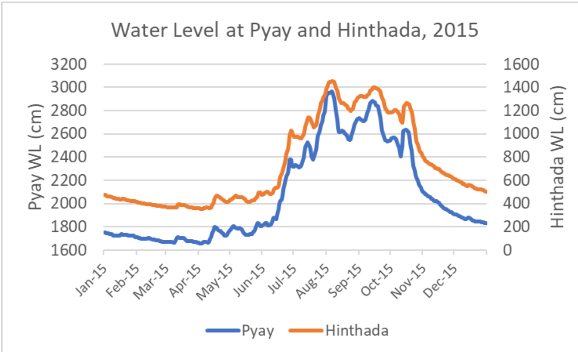


Figure 2.11 - Comparison of water level at Pyay and Hinthada (DMH)

Climate change is projected to affect the hydrology of the Ayeyarwady, through increases in temperatures and the variability and intensity of extreme weather events, and changes to rainfall patterns. Rainfall ranges are predicted to range from a decrease of 45 milimetres per month (mm month^{-1}) to an increase of up to 200 mm month^{-1} compared to the present patterns (US Aid, 2017). These types of changes will affect the geomorphology of the Ayeyarwady by altering the availability of sediment, sediment transport to the river, and the hydraulics of the river as it adjusts to altered inputs. Section 5.3.9 discusses climate change as a risk.

2.4 Strahler Order of Rivers

The Strahler Order is a measure of the complexity of river systems based on the number of tributaries feeding into a river reach. Small headwater streams have a Strahler Order of 1, while the joining of two Strahler Order 1 tributaries creates a Strahler Order 2 river reach (Strahler, 1952, 1957). The joining of a higher order (e.g. 3) with a lower order (e.g. 2) does not increase the Strahler Order downstream.

Assigning a Strahler Order is dependent on the degree of complexity of the hydrologic network used for analysis. The Greater Mekong Subregion (GMS) Core Environment[1] provides Geographic Information System (GIS) datasets of river attributes, including the Strahler Order of rivers and is commonly used to depict attributes of rivers in the Greater Mekong region. The map in

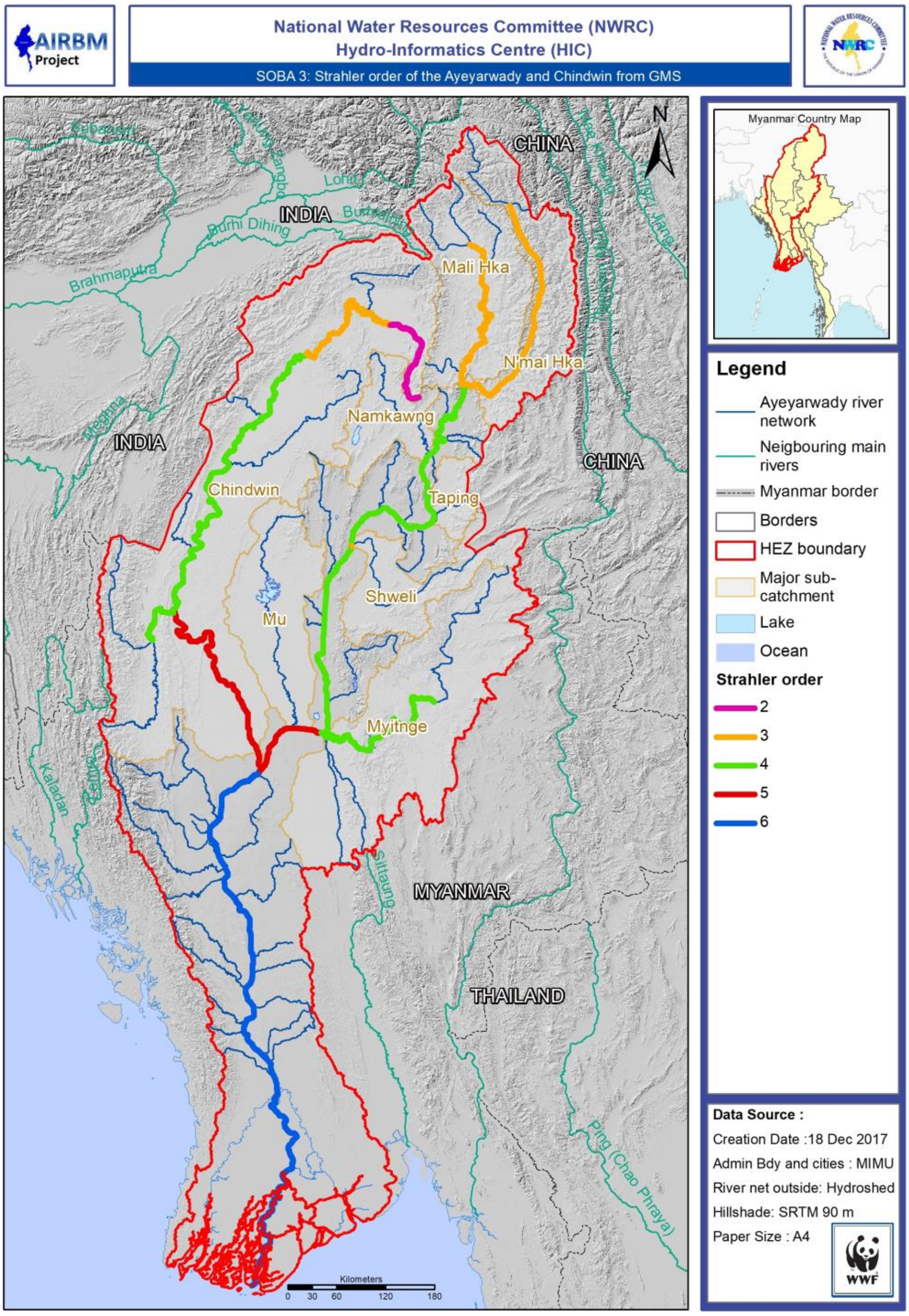
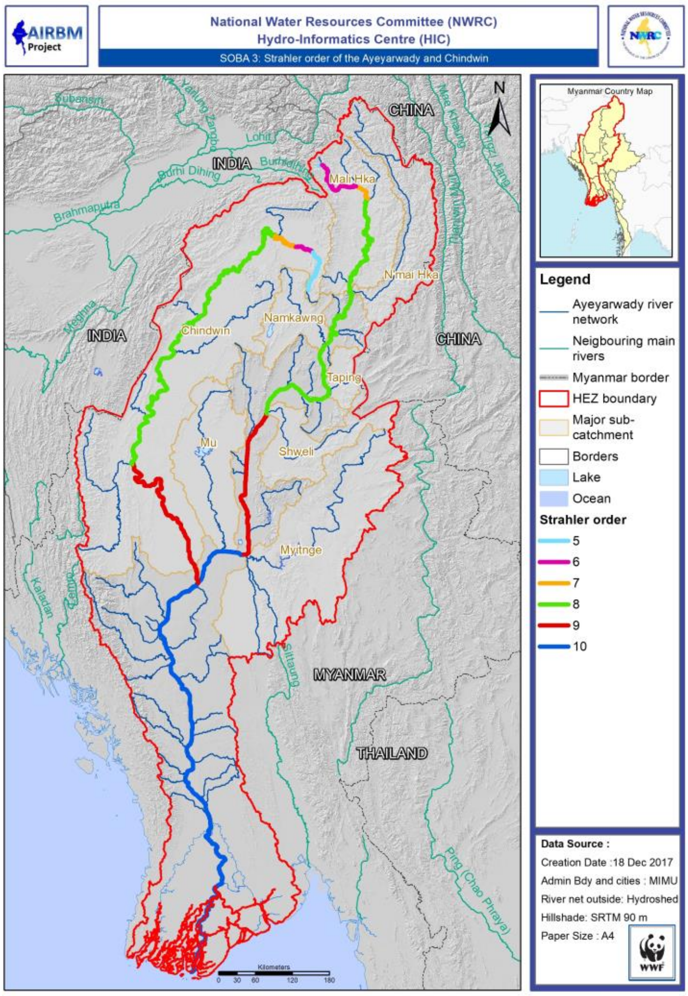


Figure 2.12 is derived from this source and shows that the main stem of the Ayeyarwady, Chindwin and lower Myitnge Rivers are all Strahler Order 4 or higher. These large rivers are the principle conduits for maintaining the connectivity of the river at a catchment scale.

[1] (http://portal.gms-eoc.org/maps)

An analysis by Bravard *et al.,* (2016) based on a combination of the SRTM and ASTER GDEM elevation grids for the region identify headwater tributaries at a much finer resolution as compared to the GMS dataset.



The Strahler Order results of this analysis (

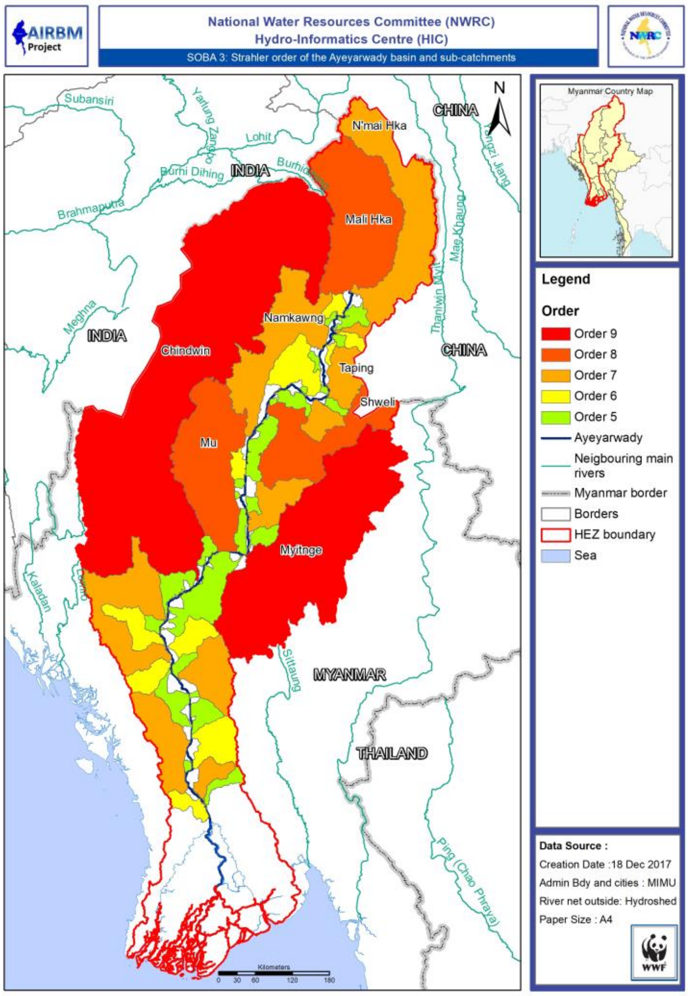


Figure 2.13) show Strahler Orders of up to 10 for the main stem of the Ayeyarwady, and 9 for the large sub-catchments of the Chindwin and Myitnge. Although the absolute values differ between the analysis, the overall pattern is the same and shows that there is a high level of complexity in the Ayeyarwady and its large tributaries.

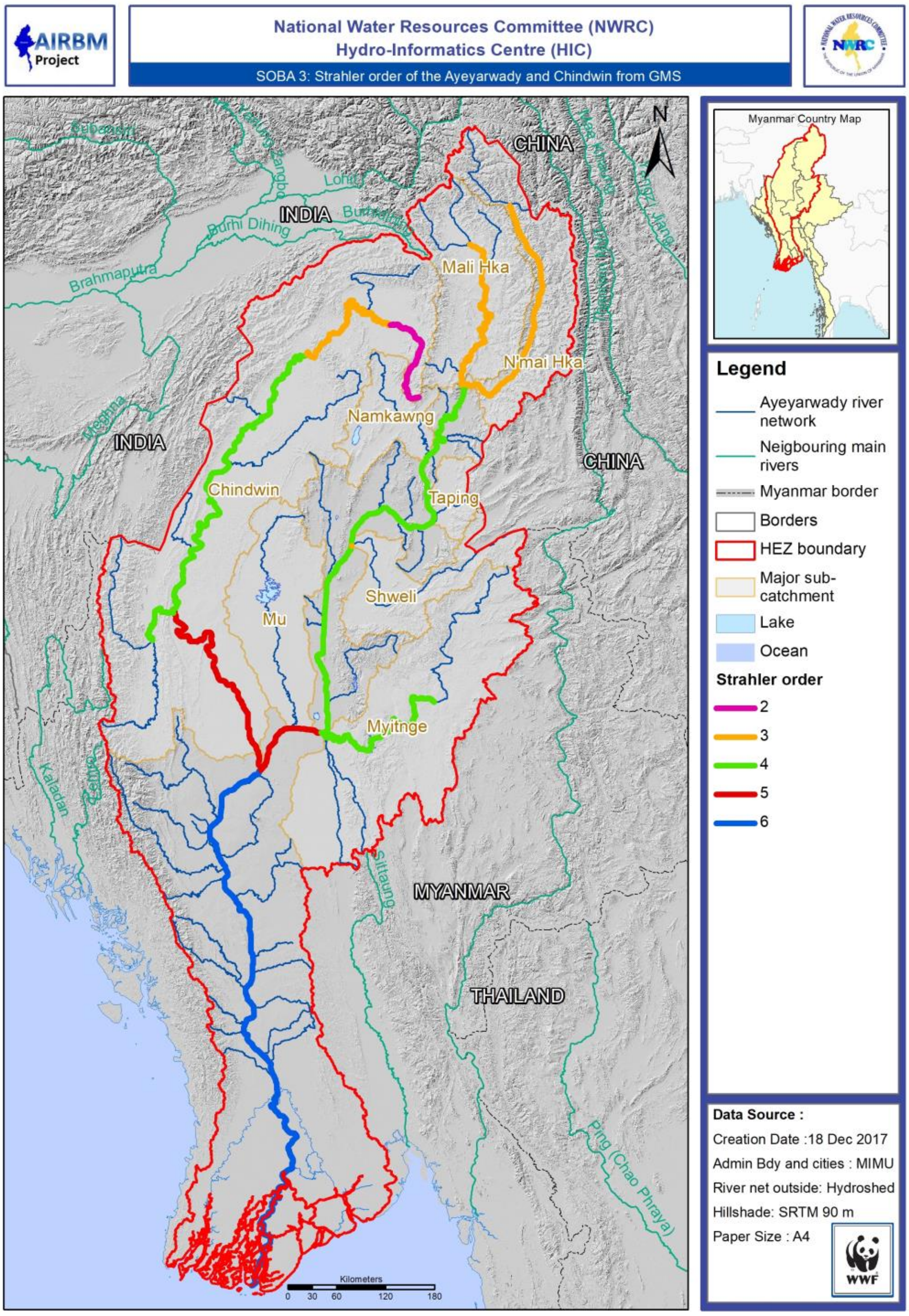


Figure 2.12 - Strahler Order of the Ayeyarwady based on the GMS GIS datasets (http://portal.gms-eoc.org/maps)

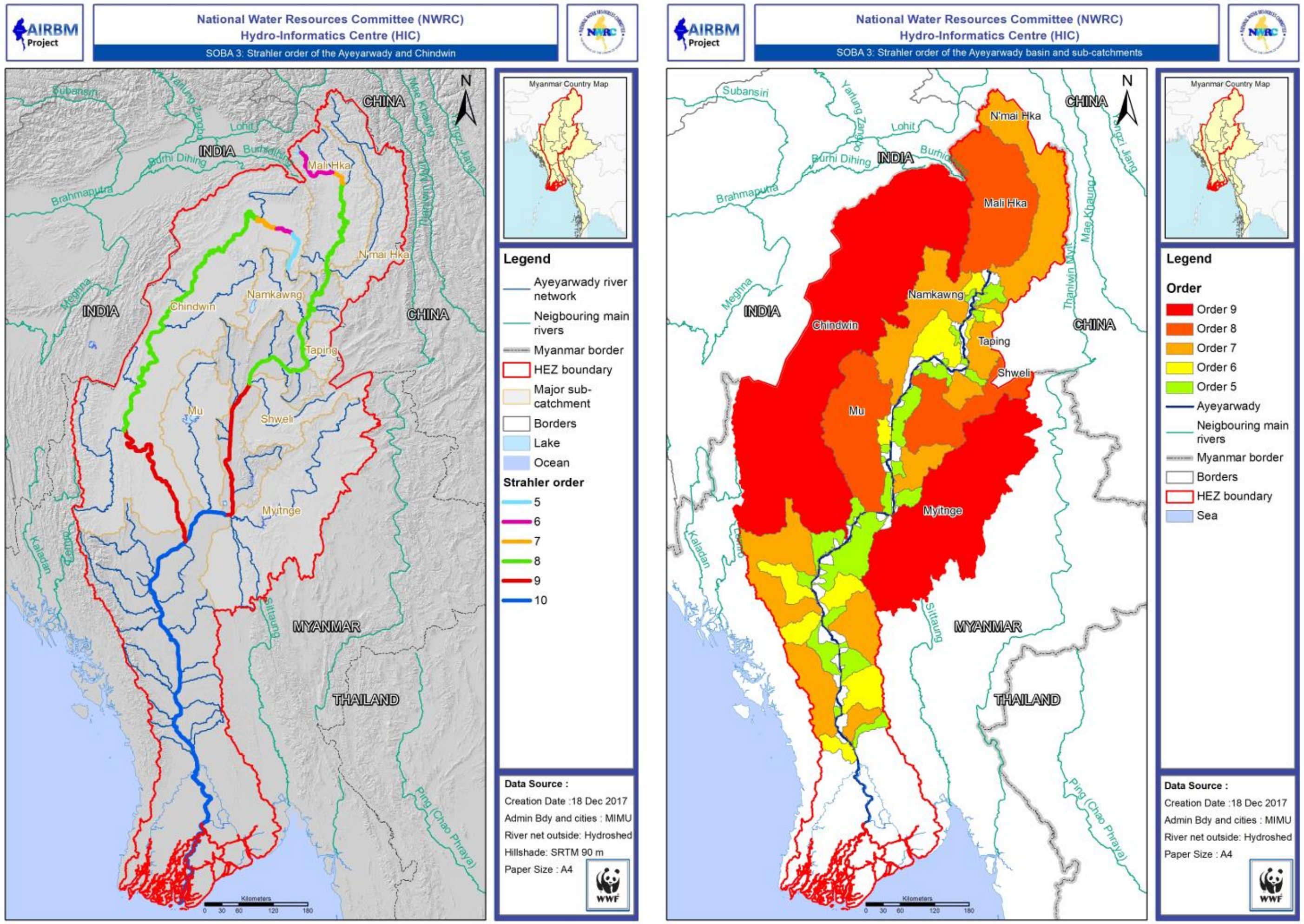


Figure 2.13 - Strahler Order analysis based on SRTM. (Source: Bravard et al., 2016)

2.5 Geomorphology of the Ayeyarwady

The landscape of the Ayeyarwady is the result of tectonic and hydrologic forces. Wang *et al.,* (2014) has comprehensively identified tectonic controls on the Ayeyarwady main stem and tributaries, with multiple tectonic systems associated with the collision of the Indian plate and Southeast Asia identified as affecting the drainage system. With respect to the characteristics of the river channels in the Ayeyarwady catchment, Lehner and Oullet-Dallaire (2014) used GIS datasets to identify and classify river segments. This classification is based on the integration of the physical attributes of the rivers, such as substrate, elevation and gradient (

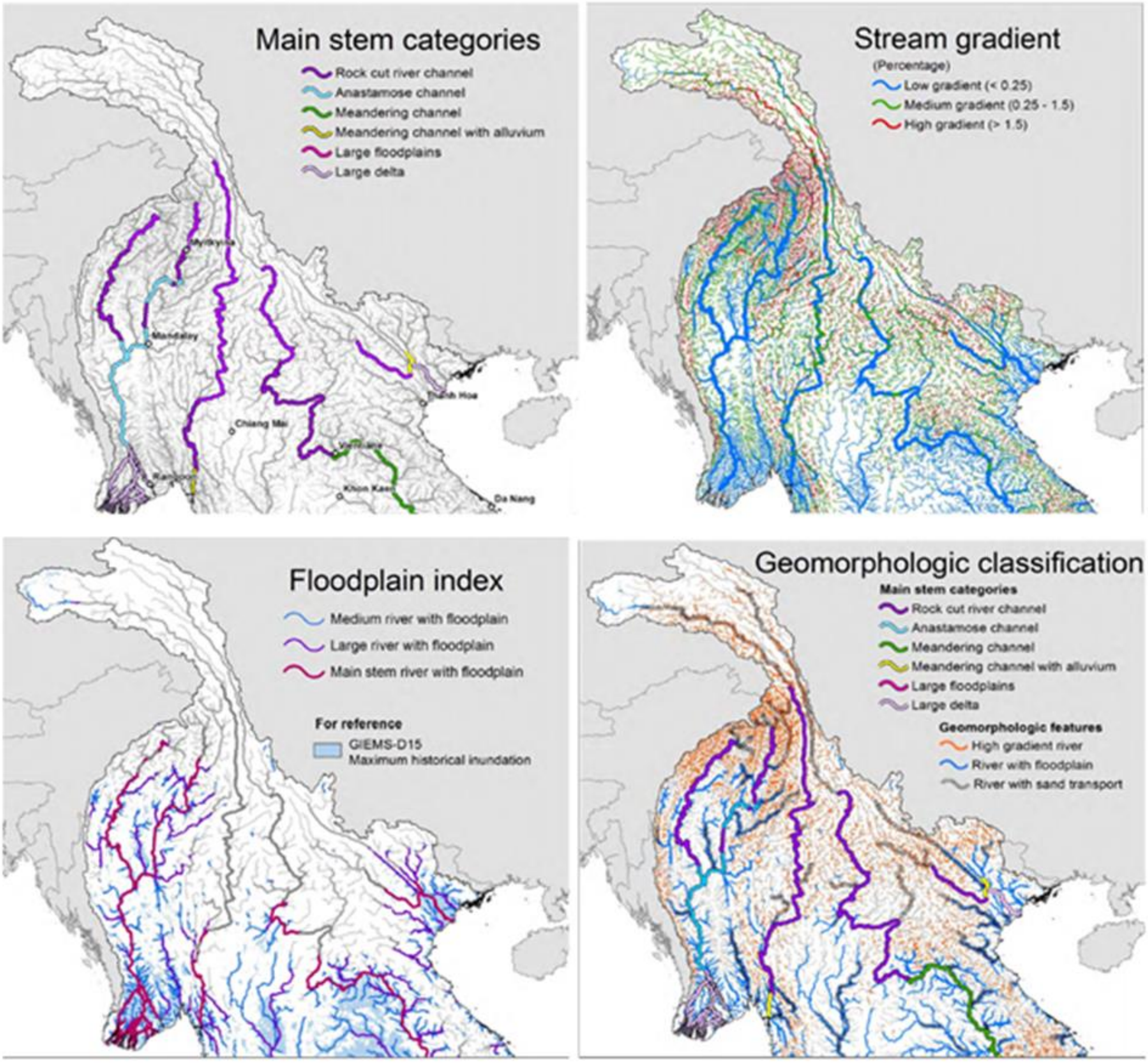


Figure 2.14). The analysis also identified the distribution of floodplains, and shows they are generally limited to the low-slope Central Basin and delta areas associated with the Ayeyarwady.

More detailed fluvial geomorphic zones along the Ayeyarwady main stem were initially identified by Bravard *et al.,* (2016) and have been adopted and built upon by the SOBA 3 Team.

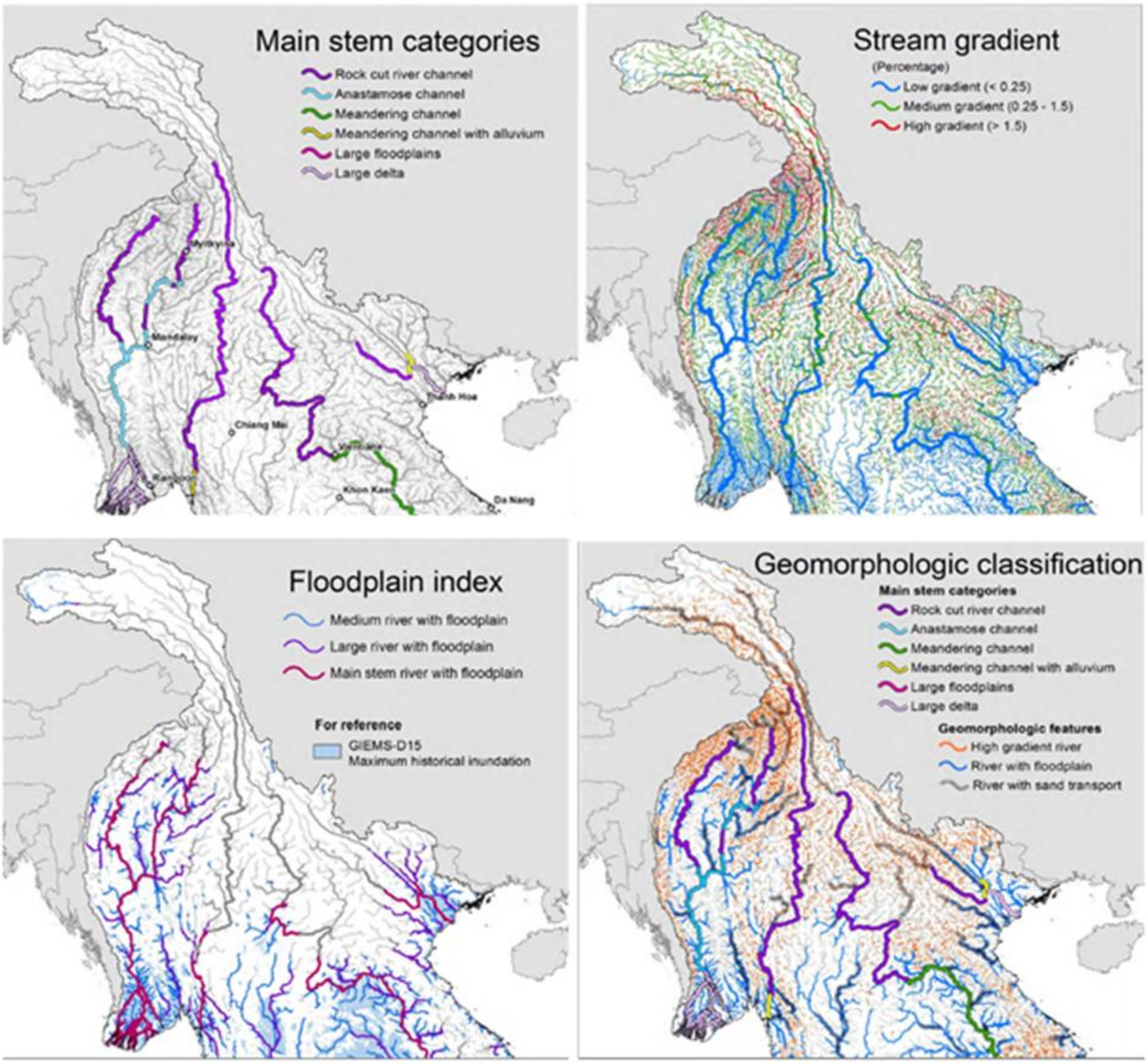


Figure 2.14 - Geomorphic attributes of river systems (Based on the GIS analysis of Lehner and Oullet-Dallaire, 2014)

2.6 Description of Geomorphic Zones

Building on a previous WWF project, SOBA 3 completes a more detailed analysis of the geomorphology of the Ayeyarwady (Bravard et al., 2016). Geomorphic zones have been identified and used as a means of describing and understanding the river, and for use in the interpretation of the sediment results. Geomorphic zones are river reaches that show similar characteristics, usually due to similar underlying geologic, landscape and hydrologic characteristics. Zone boundaries generally coincide with major hydrologic changes, such as at the confluence of major rivers like the Ayeyarwady and Chindwin, or at geologic or structural changes, such as where the river enters or exits the Sagaing fault zone. Channel characteristics reflect these landscape attributes, with narrow channels without floodplains characteristic of rivers cutting through mountainous regions, and broad meandering, multi-channelled rivers occupying wide, flat-bottomed alluvial valleys. Zone characteristics are also linked to the order in which they occur; for example, a broad open valley downstream of a steep mountainous area can be a place of sediment accumulation and storage, whereas a similar valley distant from a sediment source will be controlled by sediment reworking with little net change over time. Dividing the river into zones allows field results to be interpreted within a landscape setting, and potential impacts associated with pressures such as flow or sediment inputs to be considered at an appropriate scale.

The geomorphic zones identified for the Ayeyarwady are shown in

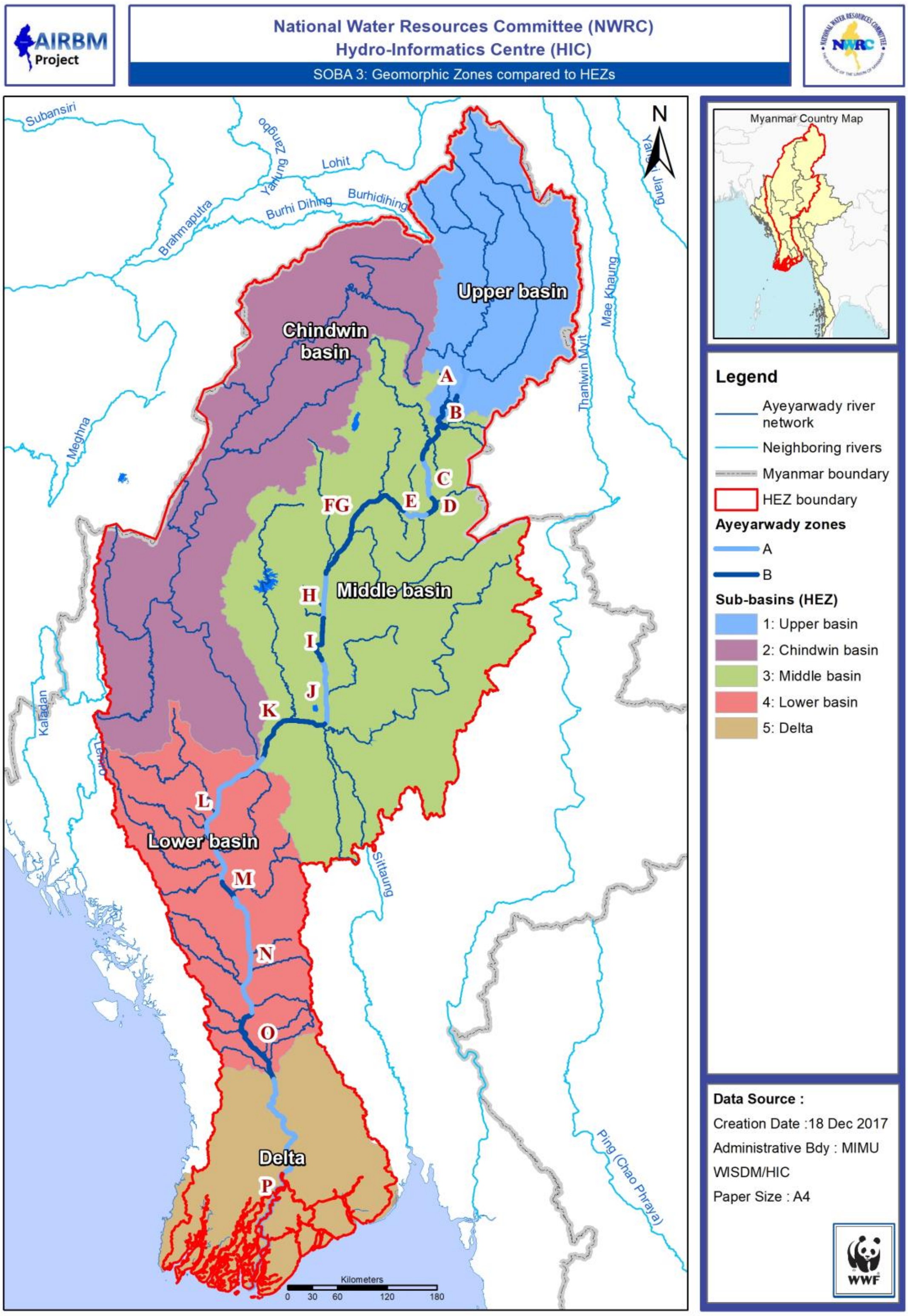
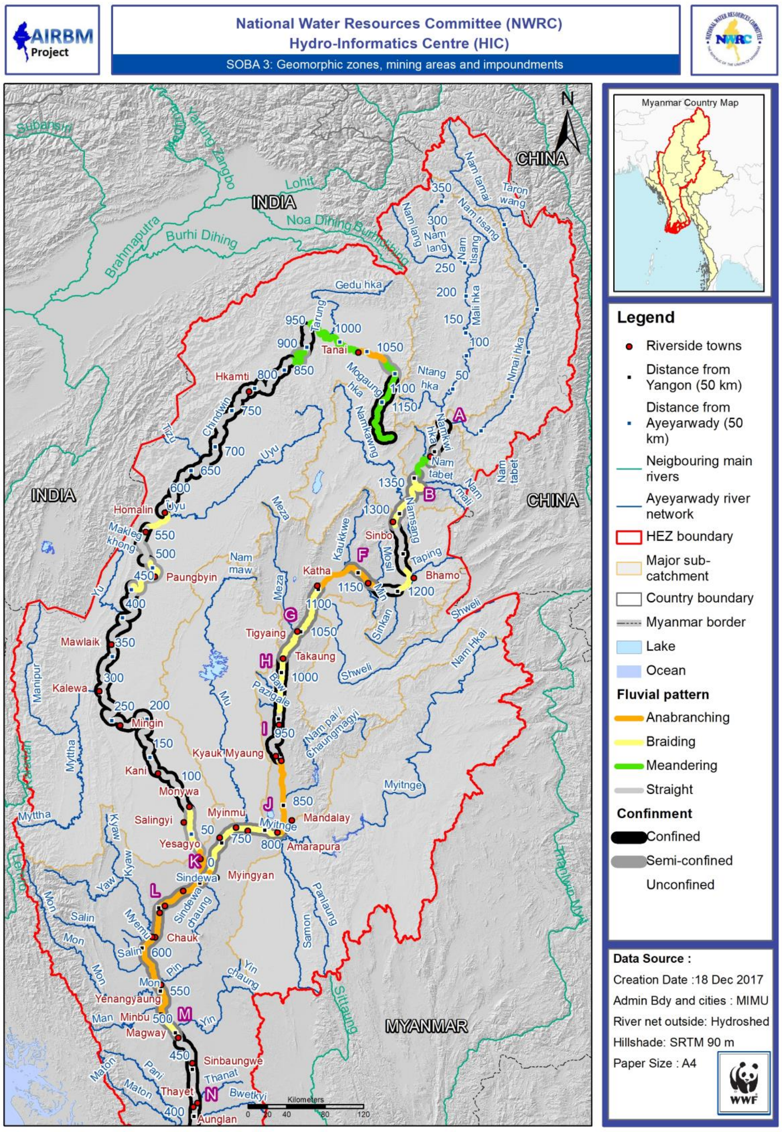


Figure 2.15, superimposed on the Hydro-Ecological Zones (HEZs) for comparison. A general description of the geomorphic zones is provided in Table 2, and in the following sections. Detailed maps of each of the zones are contained in Annex 2, along with a more detailed description of each of the zones.

The geomorphic zones correspond to the HEZs as follows: geomorphic zones Headwater (HW), zone A and part of zone B correspond to the upper Ayeyarwady HEZ; geomorphic zones B through K are incorporated in the middle Ayeyarwady HEZ; zones L through O correspond to the lower Ayeyarwady; and zone P corresponds to the delta HEZ. The SOBA 3 Team identified smaller river units as compared to the HEZ for interpretation of the sediment results as sediment transport processes vary over small spatial scales.


AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones, mining areas and impoundments
INDIA
CHINA
MYANMAR
Myanmar Country Map
Legend
Riverside towns
Distance from Yangon (50 km)
Distance from Ayeyarwady (50 km)
Neigbouring main rivers
Ayeyarwady river network
HEZ boundary
Major sub-catchment
Country boundary
Myanmar border
Lake
Ocean
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
Confinment
Confined
Semi-confined
Unconfined
Data Source :
Creation Date :18 Dec 2017
Admin Bdy and cities : MIMU
River net outside: Hydroshed
Hillshade: SRTM 90 m
Paper Size : A4
Kilometers
Hkamti
Homalin
Paungbyin
Mawlaik
Kalewa
Mingin
Kani
Monywa
Salingyi
Yesagyo
Myinmu
Myitnge
Mandalay
Amarapura
Sindewa
Myingyan
Chauk
Yenangyaung
Minbu
Magway
Sinbaungwe
Thayet
Aunglan
Tanai
Sinbo
Katha
Bhamo
Tigyaing
Takaung
Kyauk Myaung
Brahmaputra
Burhi Dihing
Lohit
Chindwin
Uyu
Meza
Mu
Shweli
Myitnge
Sittaung
WWF

As shown in

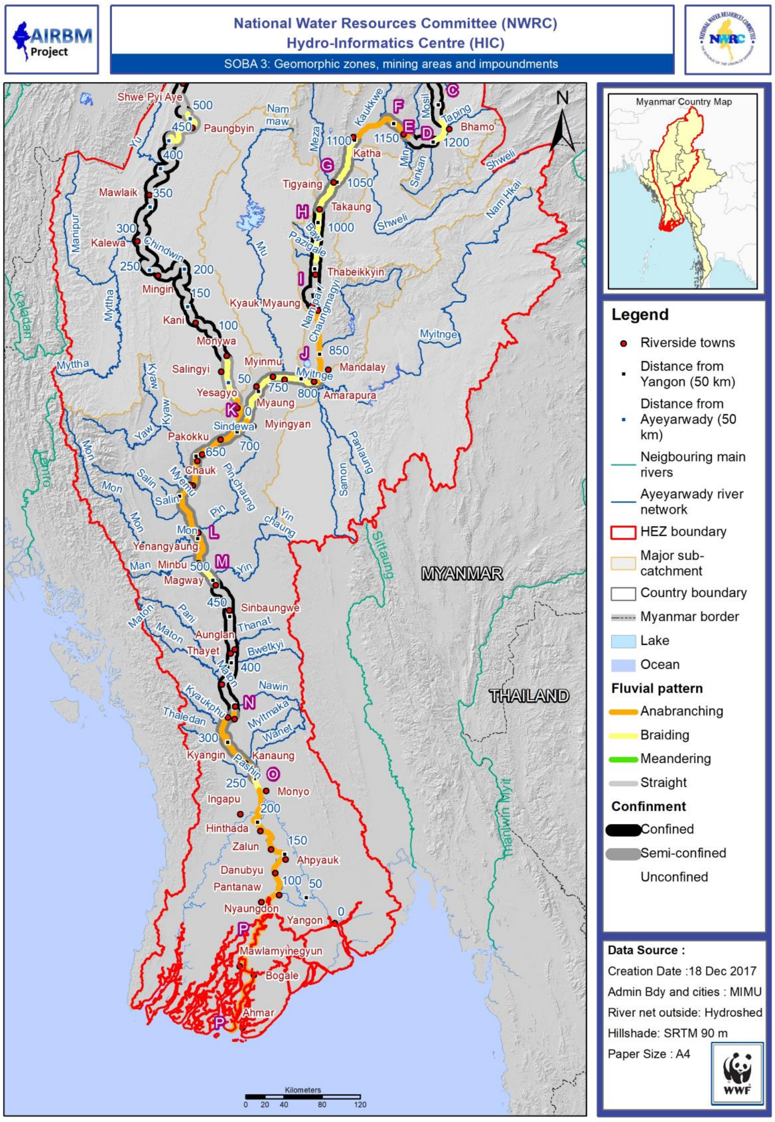


Figure 2.16, the geomorphic zones are generally based on the attributes of the main channel. These similar characteristics have also been identified for the main stem of the Chindwin, however this tributary has not been sub-divided into zones.

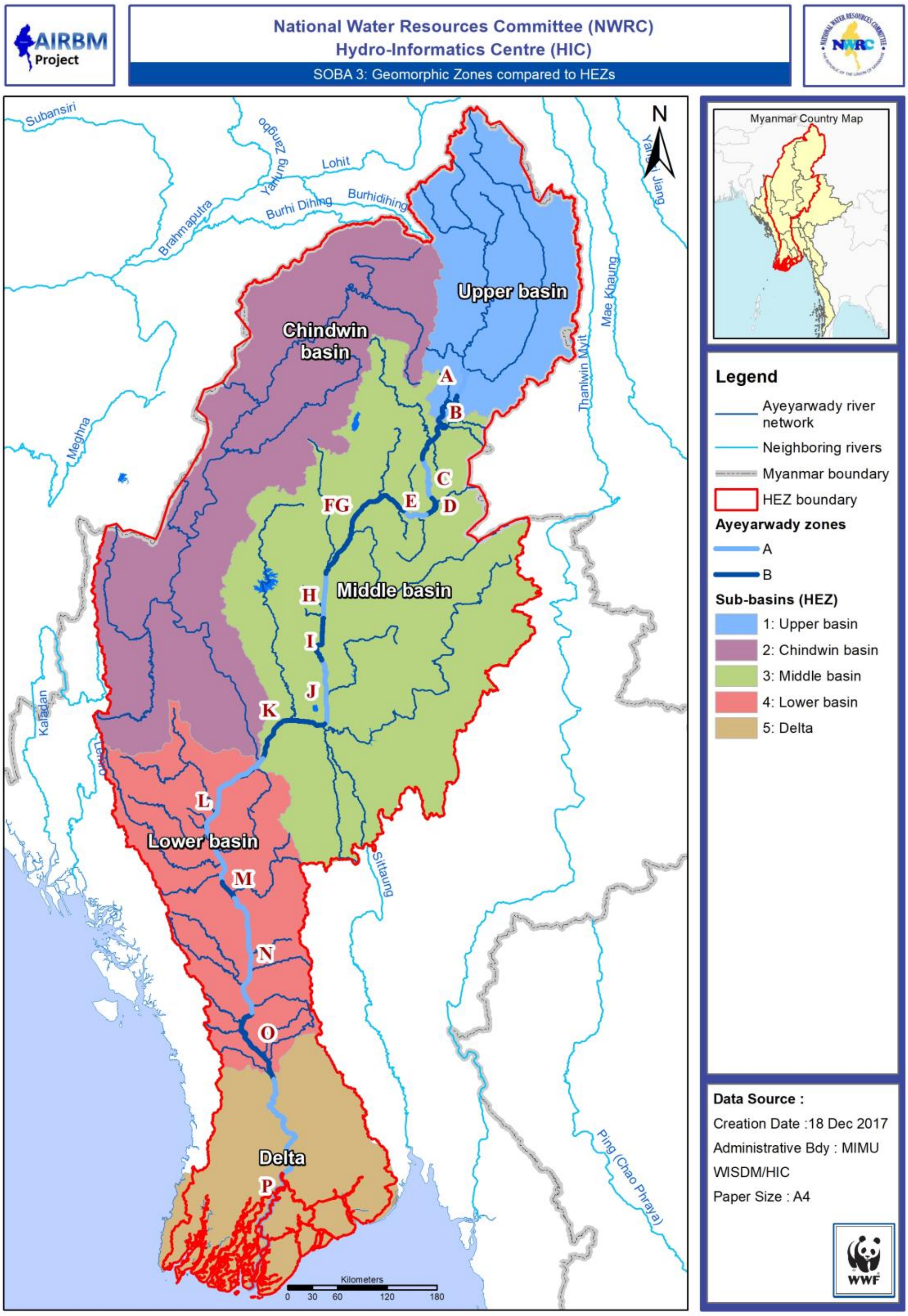


Figure 2.15 - Map of geomorphic zones used by SOBA 3 compared to Hydro-Ecological Zones

Table 2 - Summary of geomorphic zones. River kilometres are measured from the delta in an upstream direction, with 1,438 km at the confluence of the N'mai Hka and Mali Hka tributaries

Reach	River km Start/Finish (length of zone in km)	Average Slope (m km^{-2})	Pattern type
A	1400 to 1438 (38 km)	0.225	Sinuous to straight confined channel
B	1285 to 1400 (115 km)	0.130	Meandering channel in broad valley grading into a braided channel
C	1230 to 1285 (55 km)	0.143	Straight confined single channel in narrow valley
D	1201 to 1230 (29 km)	0.138	Braided channel and broad complex floodplain
E	1170 to 1201 (31 km)	0.129	Confined single bedrock channel
F	1101 to 1170 (69 km)	0.058	Anabranches (multiple channels) with multiple braided channels
G	1015 to 1101 (86 km)	0.116	Semi-confined anabranches with braided channels
H	959 to 1015 (56 km)	0.089	Braided channel within a confined valley
I	902 to 959 (57 km)	0.034	Single confined bedrock channel
J	821 to 902 (81 km)	0.111	Anabranches with multiple braided channels
K	716 to 821 (105 km)	0.076	Semi-confined braiding and local anabranching
L	523 to 716 (193 km)	0.088	Semi-confined anabranches with large braided channels
M	498 to 523 (25 km)	0.040	Semi-confined braided pattern
N	341 to 498 (157 km)	0.102	Singled confined narrow channel
O	237 to 341 (104 km)	0.079	Semi-confined discontinuous anabranching with braided channels
P	Andaman Sea -43* to 237 (280 km)	0.036	Delta distributaries

**Distances along river traditionally measured from Yangon. The coast is 43 km downstream from Yangon*

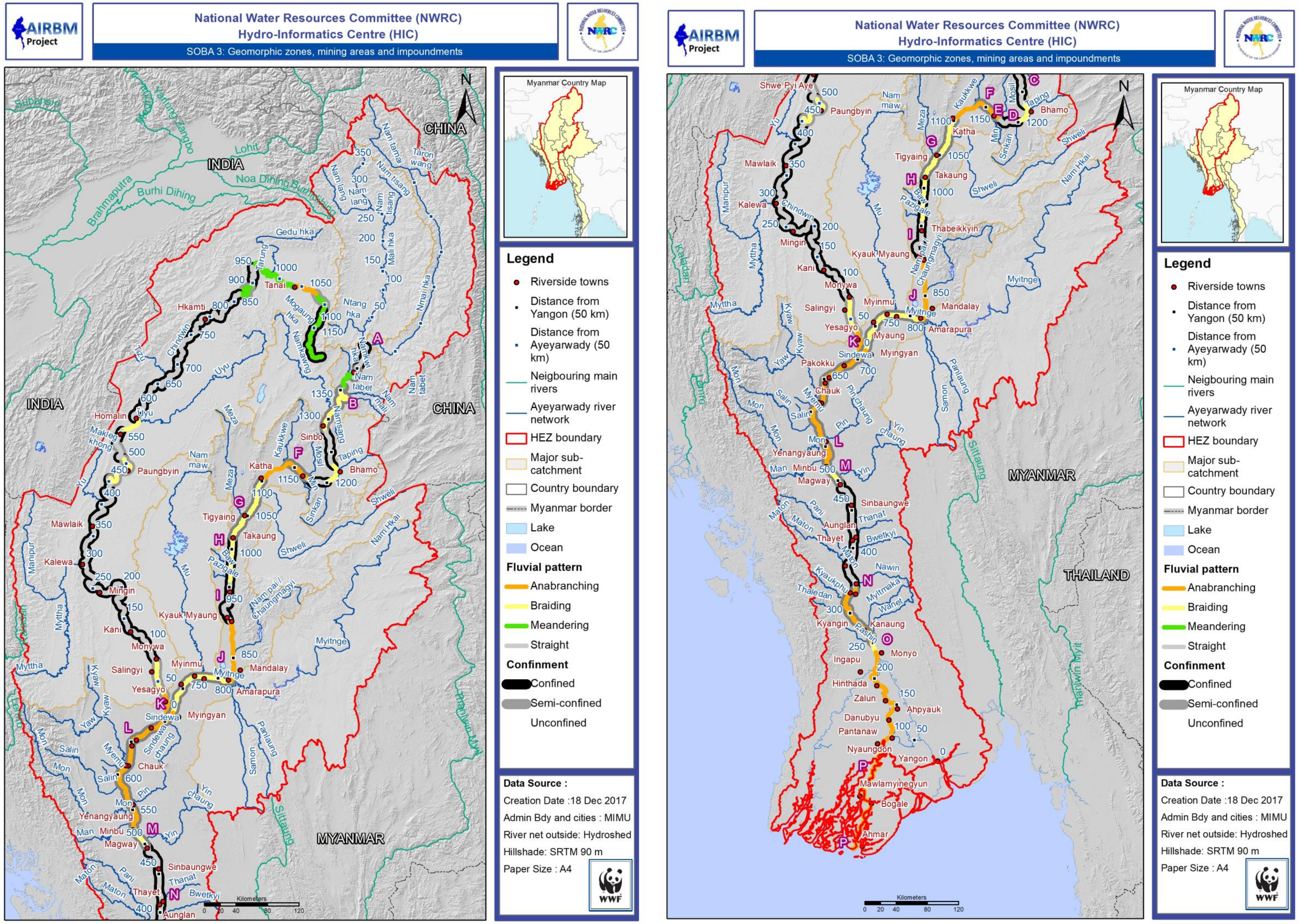
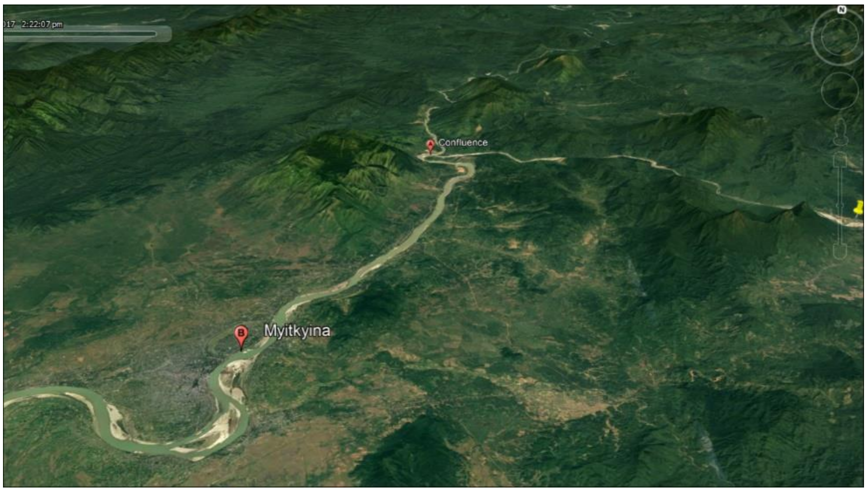


Figure 2.16 - Channel characteristics of the Ayeyarwady and Chindwin Rivers

2.6.1 Geomorphic zones

The following descriptions provide a brief overview of the characteristics of each geomorphic zone. The river flows from north (top) to south (bottom) in most photos, with markers delineating the limits of each zone[2]. Ground-based photos from the zones are included in the Field Observations section of this report (Section 4.3.1).

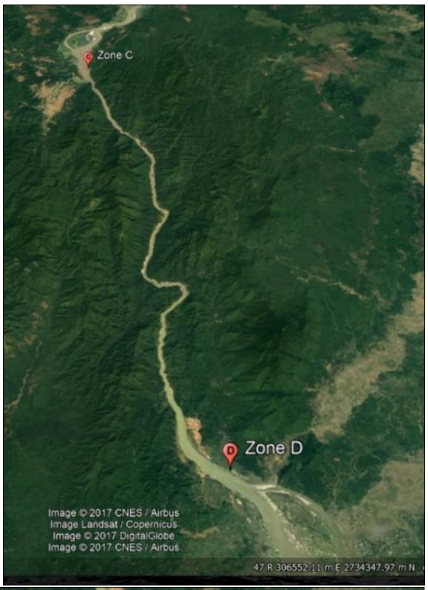
1. Zone A originates at the confluence of the N'mai Hka and Mali Hka Rivers and extends 40 km downstream to Myitkyina. The reach cuts through mountainous terrain and has the highest slope of any of the geomorphic zones. The single channel is sinuous to straight, and cobbles and boulders are present on the banks and bed of the river, reflecting its proximity to the mountains.



2. Zone B is a long zone and includes the first areas of alluvial deposition in the river. The meandering channel is unconstrained at the upstream end, flowing through a broad valley with floodplains. The valley narrows towards the downstream end and the river changes from meandering to braided, coinciding with the entrance of a tributary from the west.

[2] Photographs in this section are all from Google Earth

3. Zone C is characterised by a single narrow channel that occupies a fault lineament, cutting through a mountainous area in the Mogok Metamorphic Belt. The reach has the second highest slope of any of the geomorphic zones, and the zone is likely a throughput zone for sediments, as sediment that makes it to the top of the zone is readily transported downstream due to the higher slopes and faster water velocities. This results in little net deposition or erosion occurring within the bedrock controlled reach. Land use in the area includes gold mining that is likely to alter sediment inputs, with a disturbed area visible in the Google Earth image of the zone. No major tributaries enter in this zone.



4. Zone D is a short zone of approximately 30 km that begins about 10 km upstream of Bhamo, where the narrow bedrock channel opens up onto a broad alluvial plain. In this zone, the Ayeyarwady includes multiple branches, each of which is characterised by braiding. The left bank channel is partially constrained by the valley wall. A major tributary, the Taping, and several smaller ones enter in this reach, introducing additional flow and sediments. The reach maintains a high slope and is a very active area, with the reworking of sediment deposits resulting in rapid and frequent channel migration.

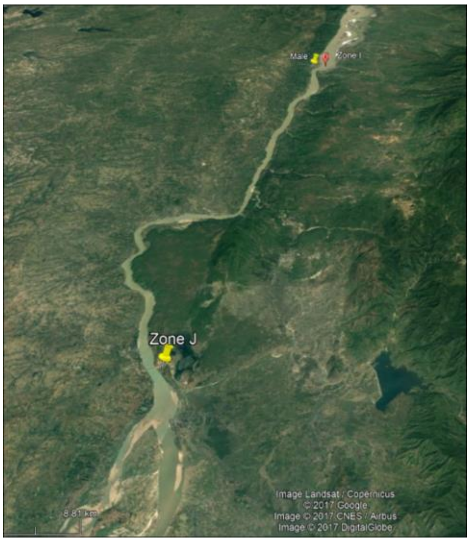
5. Zone E is a short, single channel reach that cuts through the western edge of the resilient mountain ridges associated with the Mogok Metamorphic belt. It has a deep channel and a steep slope. No major tributaries enter the Ayeyarwady in this reach. The river flows from east (right) to west (left) in the photo.

6. Zone F is a broad alluvial valley with multiple river branches (anabranches) that are each braided. The floodplain hosts a large number of small water bodies. The slope in this zone decreases to about 50% of the upstream zones, resulting in an area of high potential sediment deposition and reworking, as evidenced by high rates of channel migration. The river flows from east (right) to west (left) in the photo.

7. Zone G extends 86 km downstream of Katha through a broad north-south trending valley separating parallel ridges. Similar to the previous zone, the anabranching river has braided channels and marshy floodplains. A large tributary, the Shweli, enters via a wide floodplain, creating a mosaic of wetlands and increasing the flow and sediment load of the river.

8. Zone H is a 56 km long straight river reach confined within a narrow valley. The zone is the northern extension of where the course of the Ayeyarwady is confined to the Sagaing fault zone, accounting for its highly linear nature. The main channel lies against the elevated western wall with anabranches extending into the narrow floodplain. Terrestrial mining in the mountains east of the river introduce high loads of sediment into the river in this area.

9. Zone I includes the southern extension of where the Ayeyarwady is restricted to the Sagaing fault. At the top of Zone I, the valley is narrower and floodplain pockets are absent. The course of the river remains highly linear until it is forced to the west to flow around a resistant volcanic block. West of the fault, the river has developed floodplain pockets in the less resistant strata. At the base of the zone, the river again crosses the fault zone, emerging to an alluvial basin in the east.

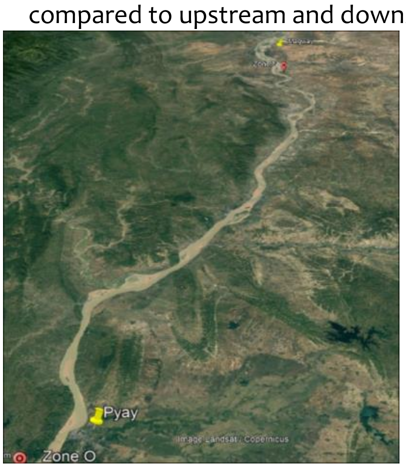


10. Zone J extends south about 75 km, from where the river enters the broad floodplain east of the Sagaing fault to upstream of Mandalay. The anabranching and braided river channels occupy a broad floodplain, that is confined on the west by the southern extension of the Sagaing fault zone, and bound on the east by the foothills of the Shan Plateau. It is an area of sediment reworking with highly mobile channels.

11. Zone K trends east to west from Mandalay to the confluence with the Chindwin River. The Ayeyarwady has a low slope through this reach and is semi-confined as it cuts through the sedimentary and metasedimentary rocks of the Irrawaddy Formation in the Eastern Trough of the Central Basin. The channel is characterised by multiple braided channels that are highly mobile.

12. Zone L is the longest zone, extending 210 km through the Central Dry Zone from the confluence of the Chinwin to near Magway. The river is semi-confined as it cuts through the western sector of the Central Basin. The channel is characterised by anabranches and braided channels and is highly active, similar to zone K. Narrow single channel reaches occur where the river cuts through ridges. Numerous small ephemeral tributaries enter the zone from both the east and west.

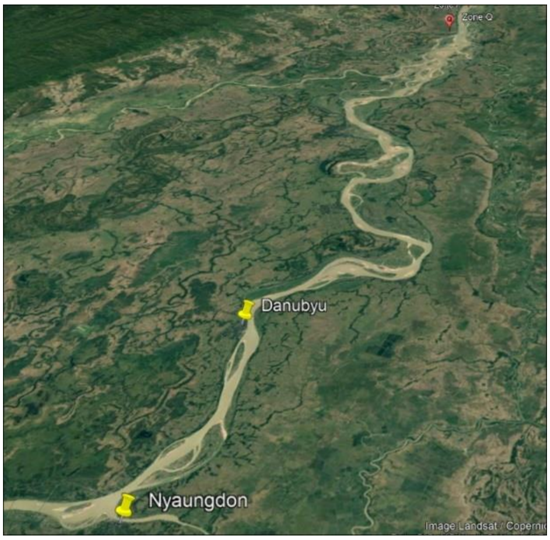
13. Zone M is a short, 25 km zone reflecting a transition from the wider valley upstream to a narrower, more confined braided river before being restricted to a single channel downstream. This reach has a lower slope as compared to upstream and downstream (RIGHT).



14. Zone N is an incised single channel reach that skirts the foothills of the Western Ranges and is confined on the east by the Pegu Hills. The zone is relatively steep for the southern Ayeyarwady (LEFT).

15. Zone O is characterised by a broadening of the river valley, with the river becoming multi-channelled and braided. The wide floodplain is pocketed with marshes and abandoned channels. This area is the southern extent of the Central Dry Zone and no major tributaries join the channel.

16. Zone P includes the final reach of the river before it separates into distributaries in the delta, and the delta. The valley widens with distance downstream, as the slope reduces. It is an area of active sediment reworking by the anabranching river. The floodplain is characterised by numerous active and non-active channels and small water bodies. Downstream of Nyaungdon, the river divides into numerous distributaries.



2.6.2 *The Ayeyarwady Delta*

The delta comprises a distinct geomorphic zone covering an area of ~35,000 km². The wedge-shaped delta extends from approximately Hinthada to the sea, but the sediments from the Ayeyarwady feed a deltaic complex extending east that includes the coastal areas of the Bago and *Sittaung* rivers. The delta is classified as a mud-silt tide dominated system with a mean tidal range of 4.2 m (Hedley et al., 2010). The west to east longshore transport along the coast carries the material into the Gulf of Martaban, which is recognised as one of the most permanently turbid areas on earth (Earth Snapshot, 2012). The area of the Ayeyarwady Delta is large for its catchment size, compared with other river catchments globally (

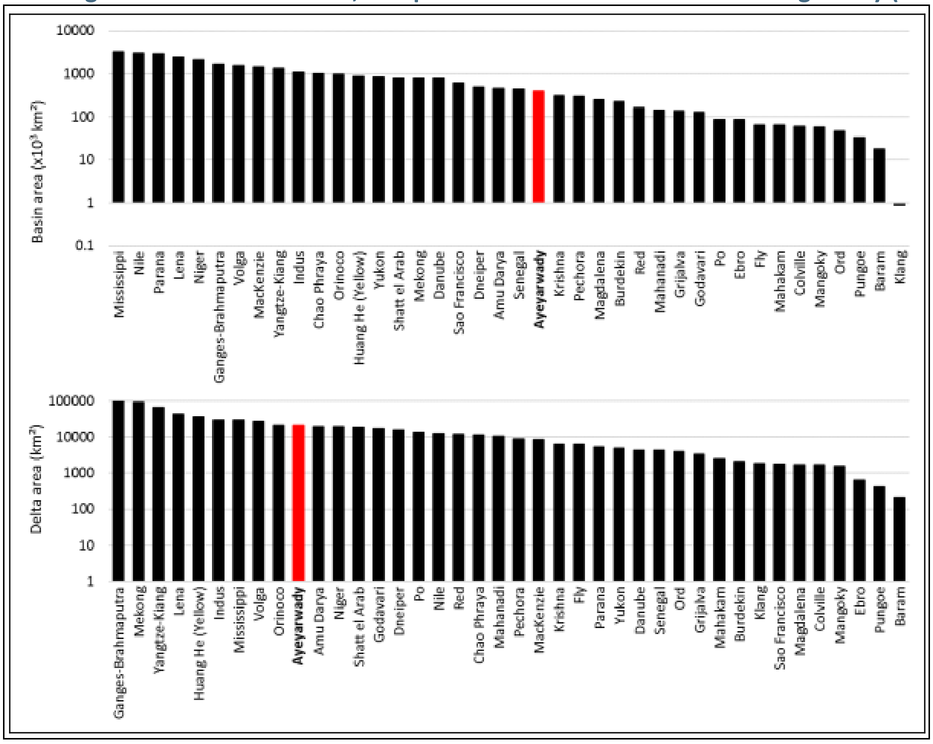


Figure 2.17). The IADS (2017) atlas compiled as part of SOBA provides an in-depth description of the delta characteristics.

The delta has existed for approximately 7,000 to 8,000 years and is characterized by extremely flat, low-lying fertile plains with five major distributaries, and innumerable additional waterways (Hedley et al., 2010). Stamp (1940) identified partially vegetated sand ridges parallel to the coast as features important for the continued progradation, as the dunes and vegetation act as silt traps. The same study suggested that the higher rainfall experienced by the southern Ayeyarwady catchment resulted in high sediment loads entering the delta region from the adjacent Arakan and Pegu 'Yomas' which were important for the continued sedimentation on the delta surface.

An analysis of historic maps and more recent satellite images by Hedley et al., (2010) concludes that the delta section of the Ayeyarwady coastline has been stable since at least 1850, with a maximum average progradation rate of 0.34 km per century. The same study suggests that since 1989, erosion has simultaneously occurred as sediment deposition along the head of the Gulf of Martaban has decreased.

Anthony et al., (2017a), examined the stability of the Ayeyarwady Delta front using satellite imagery between 1974 and 2015 combined with sediment sampling. The study found that from 1974 to 2015, erosion affected 240 out of 450 km of delta shoreline, and was greatest in large areas west of Yangon, near the mouths of the distributaries. In contrast to this trend, ongoing accretion was found in an area east of Yangon.

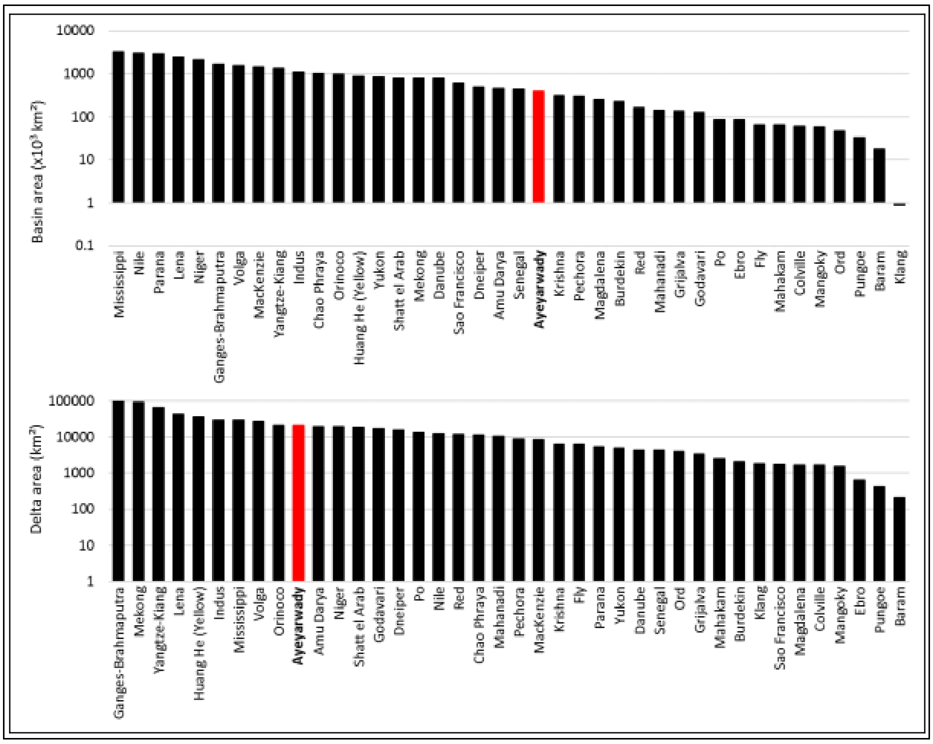
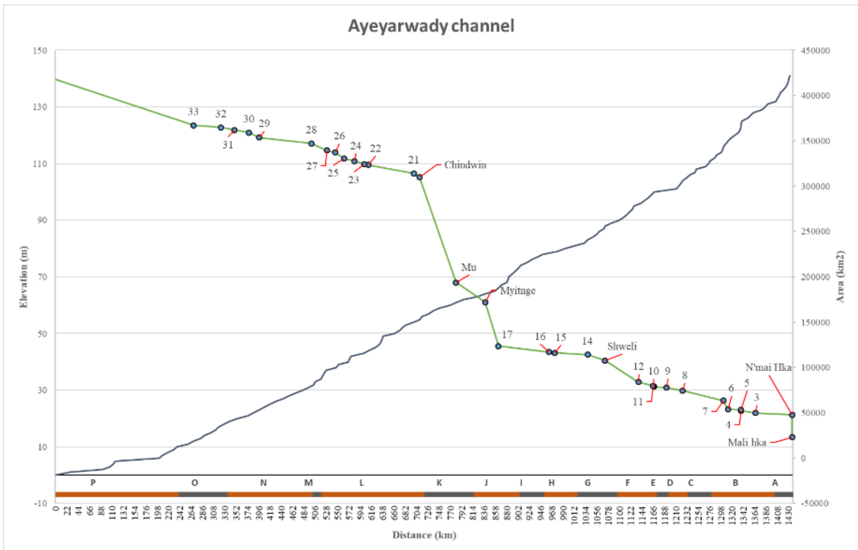


Figure 2.17 - Basin area (top) and delta area (bottom) for a selection of large rivers showing the disproportionately large size of the Ayeyarwady delta in relation to the river's catchment size compared to other rivers. *(Source: Anthony, et al., (2017a), data from Coleman and Huh ,2004)*

2.7 Large-scale River Characteristics

2.7.1 Distribution of catchment area

The distribution of catchment area along the Ayeyarwady main stem is shown in

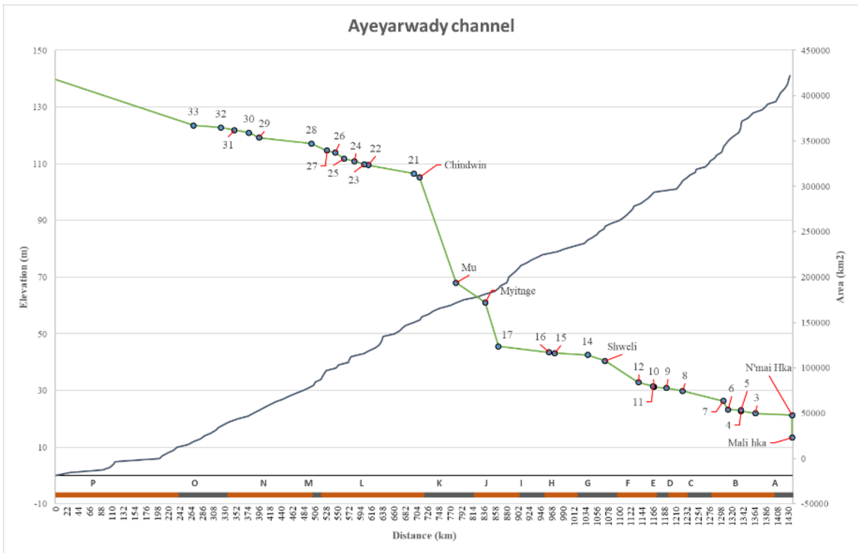


No.	River	No	River
1	Mali hka	18	Myitnge
2	N'mai hka	19	Mu
3	Namkwi hka	20	Chindwin
4	Nam tabet	21	Sindewa
5	Nam mali	22	Yaw
6	Namsang	23	Myemu
7	Namkawng	24	Salin
8	Taping	25	Pin
9	Sinkan	26	Mon
10	Mosil	27	Man
11	Min	28	Yin
12	Kaukkwe	29	Bwetkyi
13	Shweli	30	Maton
14	Meza	31	Nawin
15	Baw	32	Kyaukphu
16	Pazigale	33	Myltmaka
17	Nam pai		

Figure 2.18. The catchment area shows uniform and similar increases in the upper area of the catchment, between the Mali Hka and N'mai Hka and the Nam Pai, and in the lower river, between the Chindwin and the Myltmaka. The middle Ayeyarwady experiences a very large increase in catchment area over a short distance, with the Mytinge, Mu and Chindwin tributaries all entering within a short, ~155 km length of the river. The

entrance of these three large sub-catchments more than doubles the area of the Ayeyarwady from ~123,500 km^2 to 310,200 km^2. The Ayeyarwady downstream of this area will be affected by the flow and sediment inputs from these large tributaries, as well as from the Ayeyarwady upstream of the Myitnge. It is important to note that flow in the Myitnge is regulated by multiple hydropower plants, including the large Yewya project, and that flow in the Mu is regulated through the multi-use Thapanzeik hydropower and irrigation scheme. These developments are discussed in more detail in Section 3.3.

The current flow data for the Ayeyarwady do not provide a consistent balance across the catchment (Alluvium and Hydronumerics, 2017), so the distribution of flow input cannot be accurately quantified. However, based on the estimations of Rocha and Wilkinson (2017; see Section 2.3.1), the Chindwin and upper Ayeyarwady provide the majority of flow to the Ayeyarwady, with the catchment area downstream of Sagaing (excluding the Chindwin) providing low volumes of water due to low rainfall and runoff totals.



No.	River	No	River
1	Mali hka	18	Myitnge
2	N'mai hka	19	Mu
3	Namkwi hka	20	Chindwin
4	Nam tabet	21	Sindewa
5	Nam mali	22	Yaw
6	Namsang	23	Myemu
7	Namkawng	24	Salin
8	Taping	25	Pin
9	Sinkan	26	Mon
10	Mosil	27	Man
11	Min	28	Yin
12	Kaukkwe	29	Bwetkyi
13	Shweli	30	Maton
14	Meza	31	Nawin
15	Baw	32	Kyaukphu
16	Pazigale	33	Myltmaka
17	Nam pai		

Figure 2.18 - Elevation of the Ayeyarwady River and catchment area
The left axis shows the elevation of the main stem of the Ayeyarwady, while the right axis shows the cumulative catchment area of the river. The locations of tributary confluences are indicated on the area.

2.8 Ayeyarwady Long Section and Tributary Slopes

A long section showing the slope of the Ayeyarwady with distance upstream from the sea (

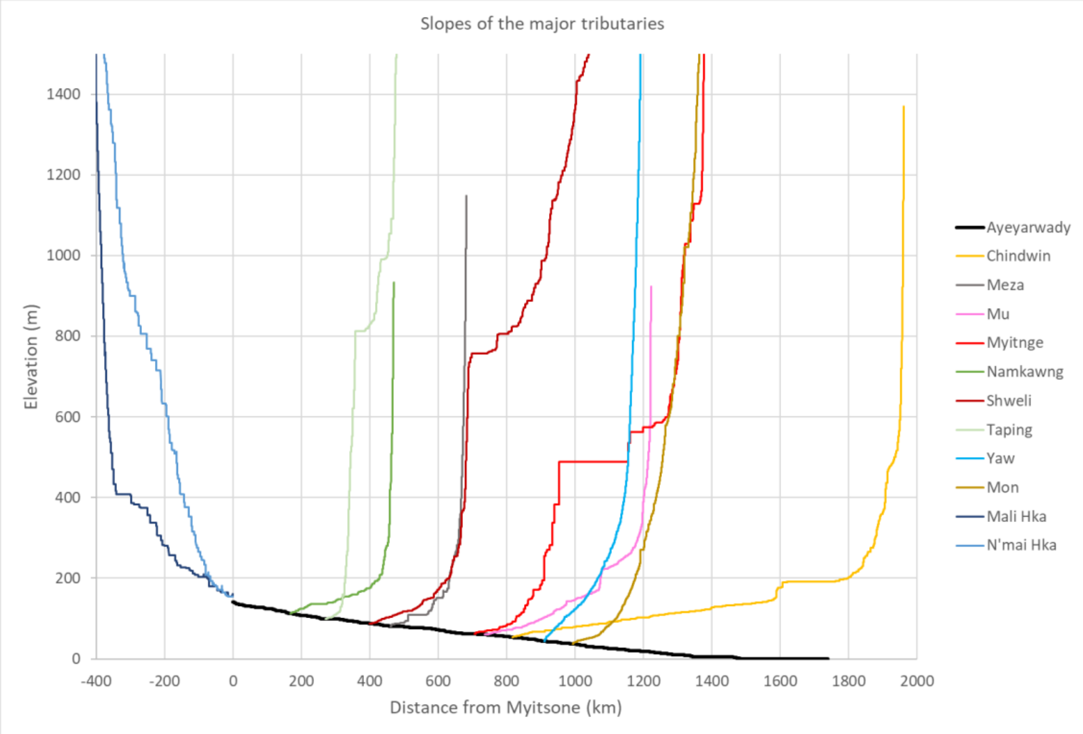


Figure 2.19) shows that the slope of the river varies, but there are no major 'knick points' or reaches where the slope differs dramatically from upstream or downstream. The slope of the Ayeyarwady progressively decreases over its 1750 km course between the headwaters and the delta (

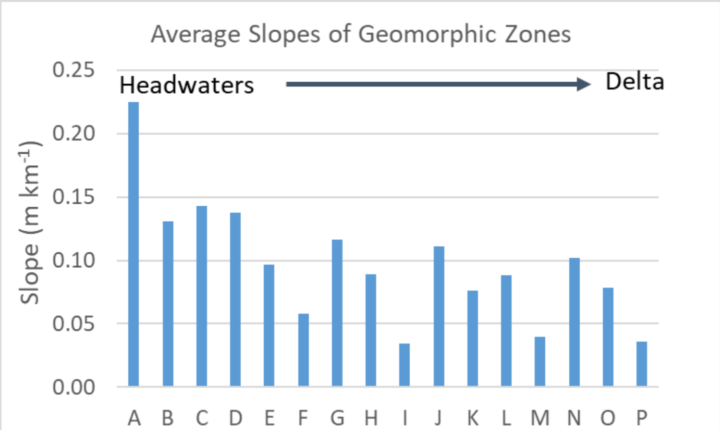


Figure 2.20), with the zones consisting of broad valleys with alluvial fill generally having lower slopes. The headwater areas of the Mali Hka and N'mai Hka have much higher slopes than the main stem downstream of the confluence. Tributaries show greater variability as compared to the main stem, with the differences linked to the geology and topography of the headwater source (

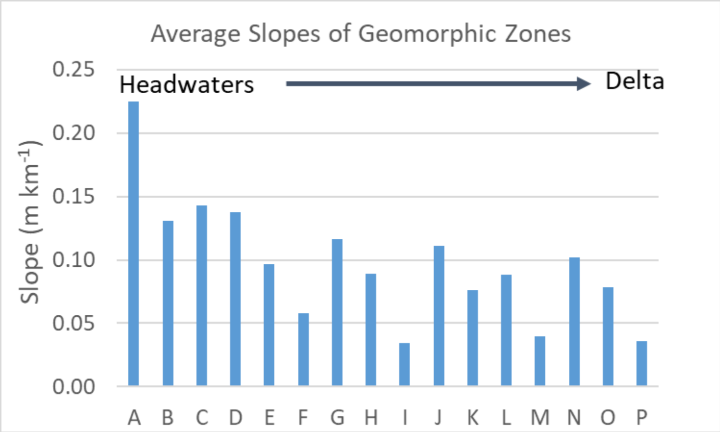


Figure 2.20). Understanding the attributes of the tributaries assists in understanding sediment transport, as steeper tributaries have the potential to deliver coarser material to the main stem of the Ayeyarwady as compared to the tributaries with lower slopes.

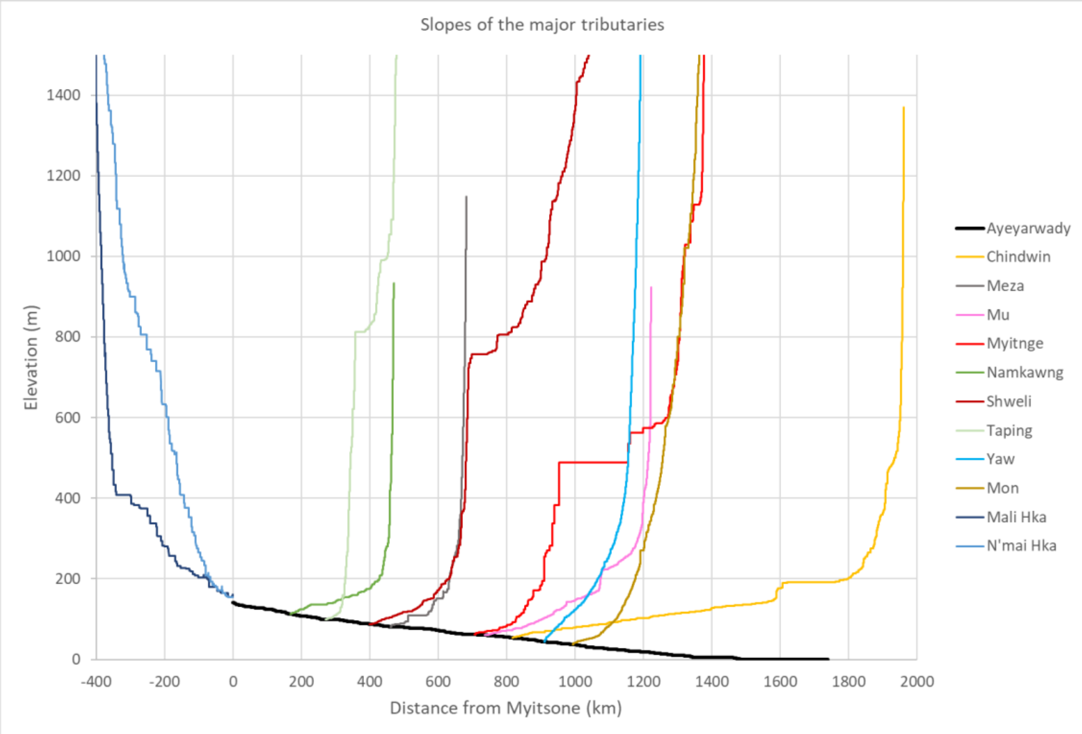


Figure 2.19 - Long-section of the Ayeyarwady River and tributaries
Graph shows slope of the Ayeyarwady, and location and slope of major tributaries. Distances measured from confluence of N'mai Hka and Mali Hka Rivers (Myitsone)

.

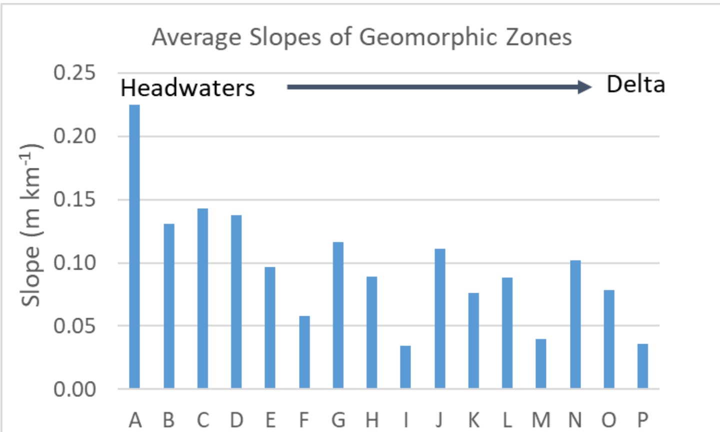


Figure 2.20 - Average slope of the Ayeyarwady main stem by geomorphic zone

2.8.1 Channel width

The width of the Ayeyarwady channel was determined using satellite imagery, which reflects the average width of the river over the wet and dry seasons. Details of the method used are contained in Annex 3. Channel width varies with distance downstream depending on the nature of the valley. Areas cutting through resilient bedrock will have narrower channels as compared to areas where the river occupies a broad alluvial valley. Like most rivers, the Ayeyarwady consists of a sequence of narrow channels opening to larger ones before being constricted again, which coincides with the river cutting its way through the mountains and hills of the upper catchment. As the river progresses downstream, the valley becomes predominantly alluvial, allowing the river to move and occupy broader areas. This accounts for the general increase in channel width with distance downstream.

The Chindwin River has an overall narrower channel that increases from the headwaters to the confluence with the Ayeyarwady. The majority of the channel is characterised as a single channel with limited areas of braiding. Meandering river reaches are limited to the upper areas of both rivers.

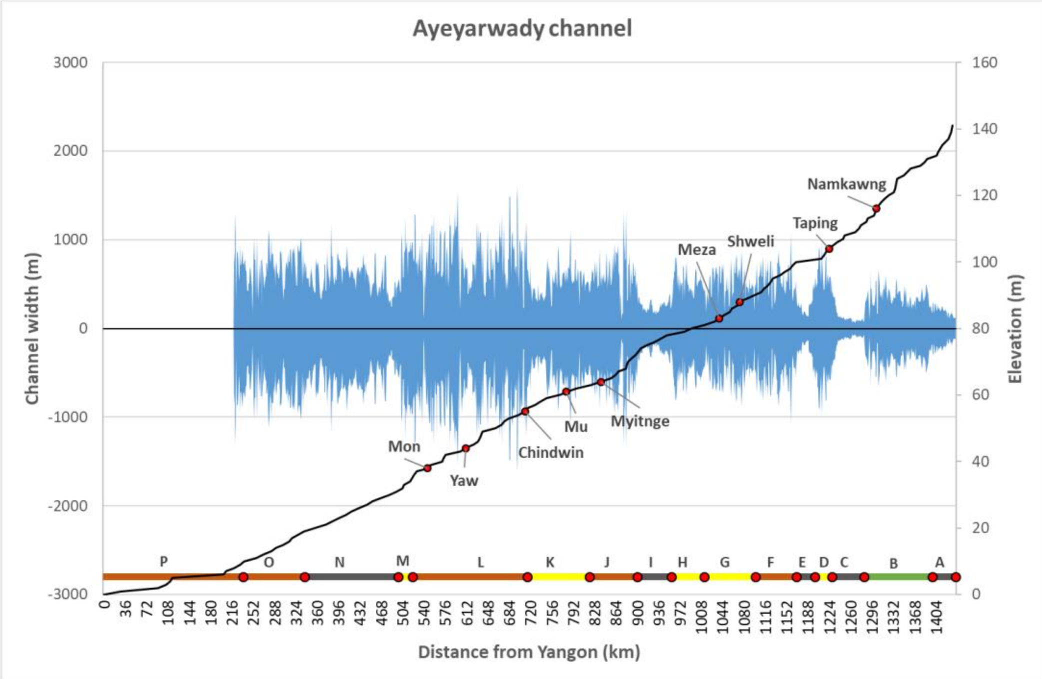


Figure 2.21 - Average channel width of the Ayeyarwady River
Figures show the average width of the channel on the left and the elevation of the long-section of the river on the right axis. Confluences of tributaries are indicated. Colours along x-axis correspond to channel type: gray = single channel, green = meandering, yellow = braided, and orange = anabranching. (Based on satellite analysis as described in Annex 3.)

No.	Tributaries
1	Tabyi Hka
2	Tawang Hka
3	Tarung Hka
4	Taga Hka
5	Tagum Hka
6	Tampuk Hka
7	Nom Tonhtun
8	Nantaleik
9	Uyu
10	Mu
11	Yu
12	Kodan
13	Myittha
14	Taungdwin
15	Patolon
16	Thanbaul
17	Yewa
18	Yama

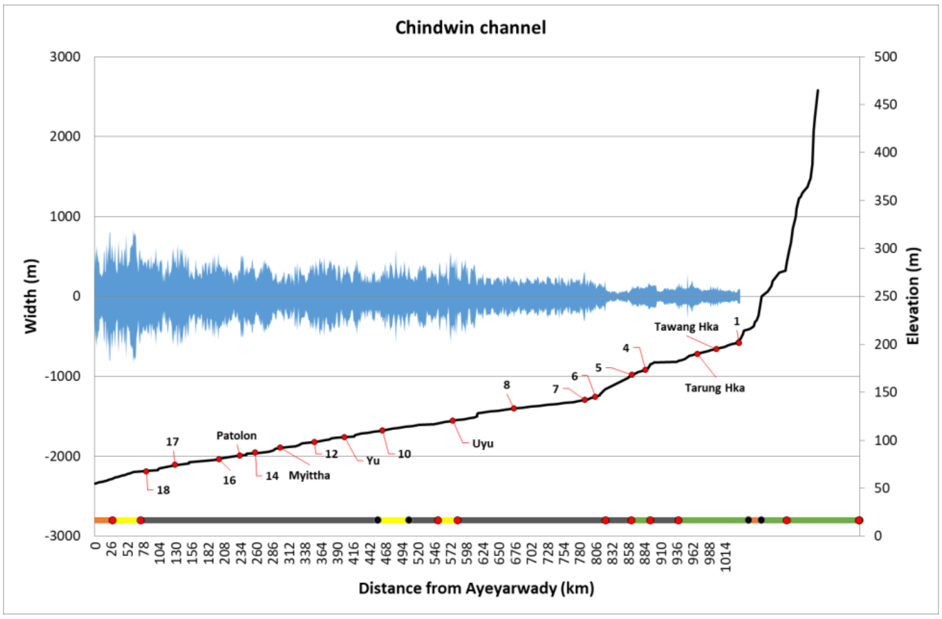


Figure 2.22 - Similar Figure as

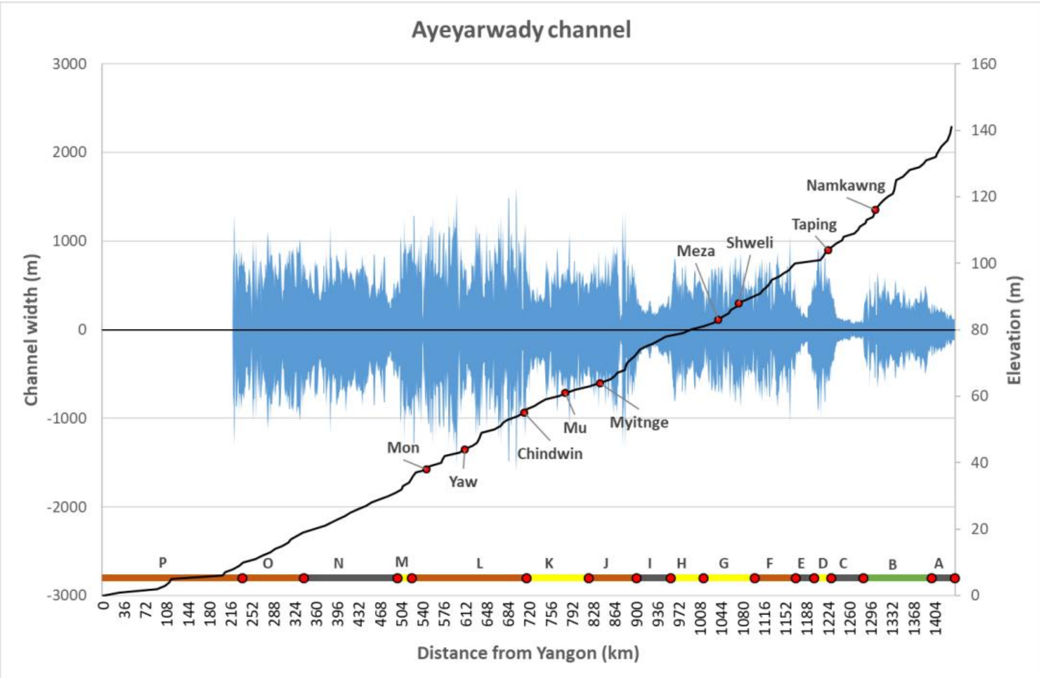


Figure 2.21 for the Chindwin River.
Tributaries shown in table on the right.

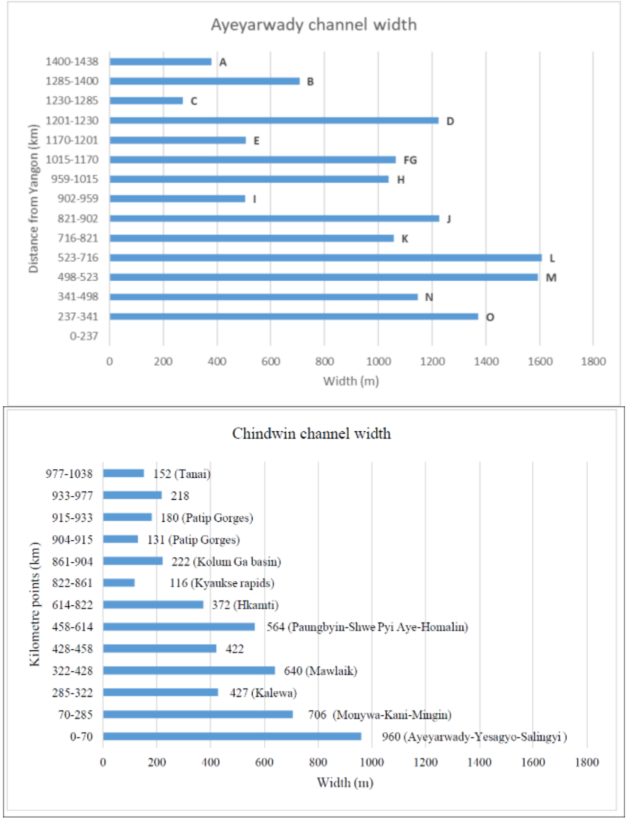
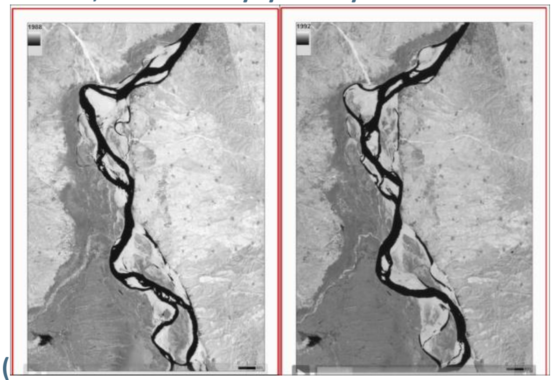


Figure 2.23 - (Left) Summary of average channel width on the Ayeyarwady River by geomorphic zones and (Right) of the Chindwin River for indicated reaches

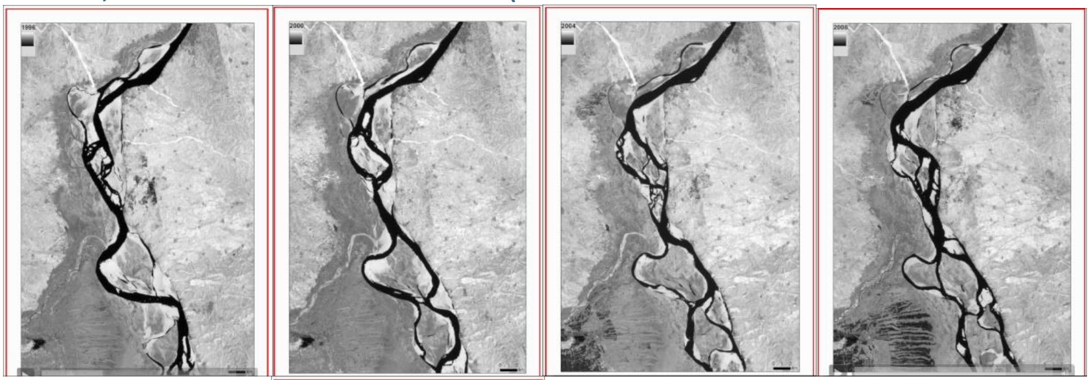
2.8.2 *Channel mobility*

Much of the length of the Ayeyarwady is prone to channel changes and migration, as the river is unconstrained and has relatively low slopes and high sediment loads. Areas prone to channel changes include geomorphic zones B, D, F, G, H, and J upstream of Mandalay, and all zones downstream of Mandalay with the exception of N and O. Channel migration presents challenges and risks for navigation, access and shore-based infrastructure, due to the potential for shifting channels to cause erosion and undermine structures.

Examples of channel migration are shown for two areas; one in the Ayeyarwady River downstream of



Chauk, and one in the delta near Hinthada (



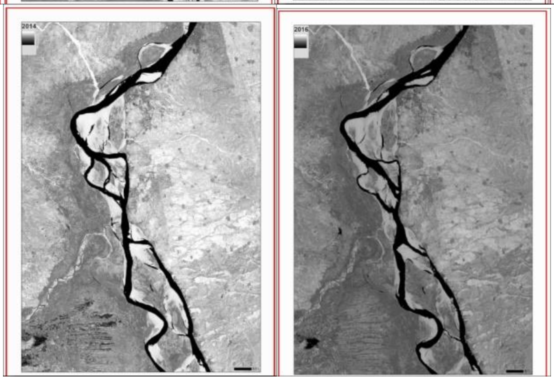


Figure 2.24 and

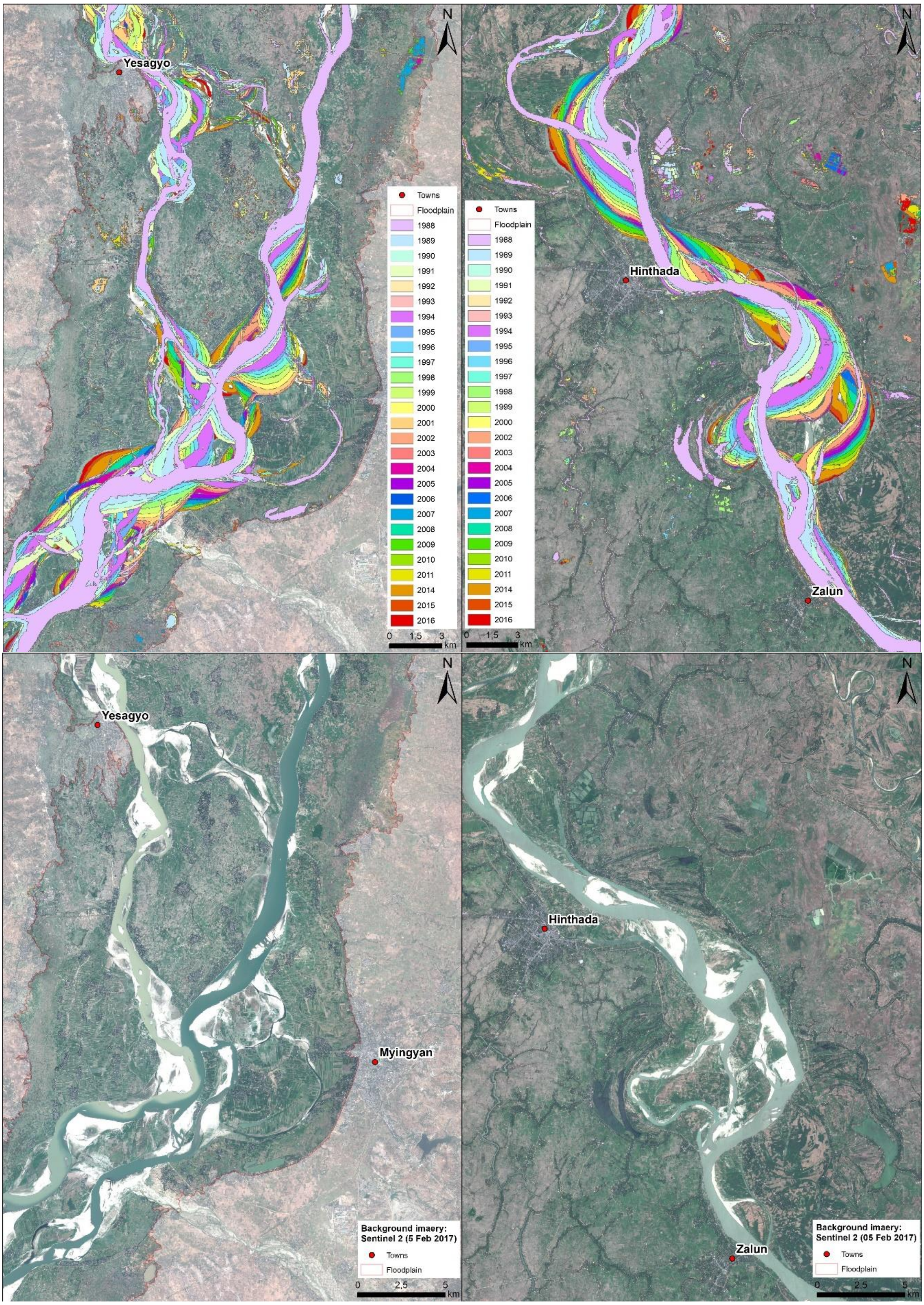


Figure 2.25). Channel changes can occur gradually, such as in the lateral migration of meanders within the delta setting, or the abandonment of the western channel in the Ayeyarwady sequence, which is indicated by a red star on the first photo of the sequence. Channel changes also occur abruptly, typically during high flow events, such as in July 2017, when flood flows altered the course of the river near Magway, and

resulted in extensive bank erosion, including the loss of a pagoda (

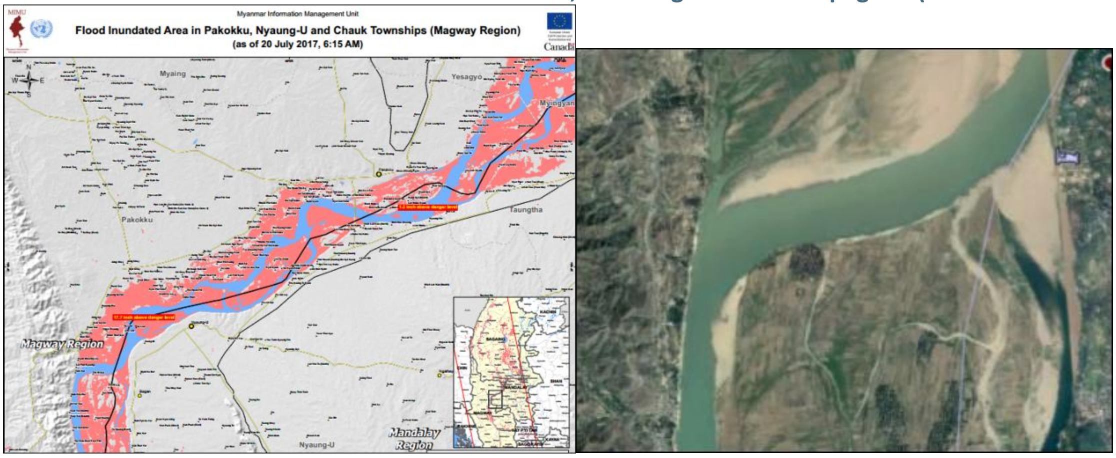


Figure 2.26). At the time of the major bank collapse, water level in the river exceeded the danger level by ~30 cm. The area is hydraulically complex, with the river having to turn sharply southward due to the resilient north-south trending hills. Numerous small channels are evident in imagery taken in February 2017, and it is likely that at very high flow the channel was activated, and the force of water entering the channel eroded the downstream bank where the pagoda was located (

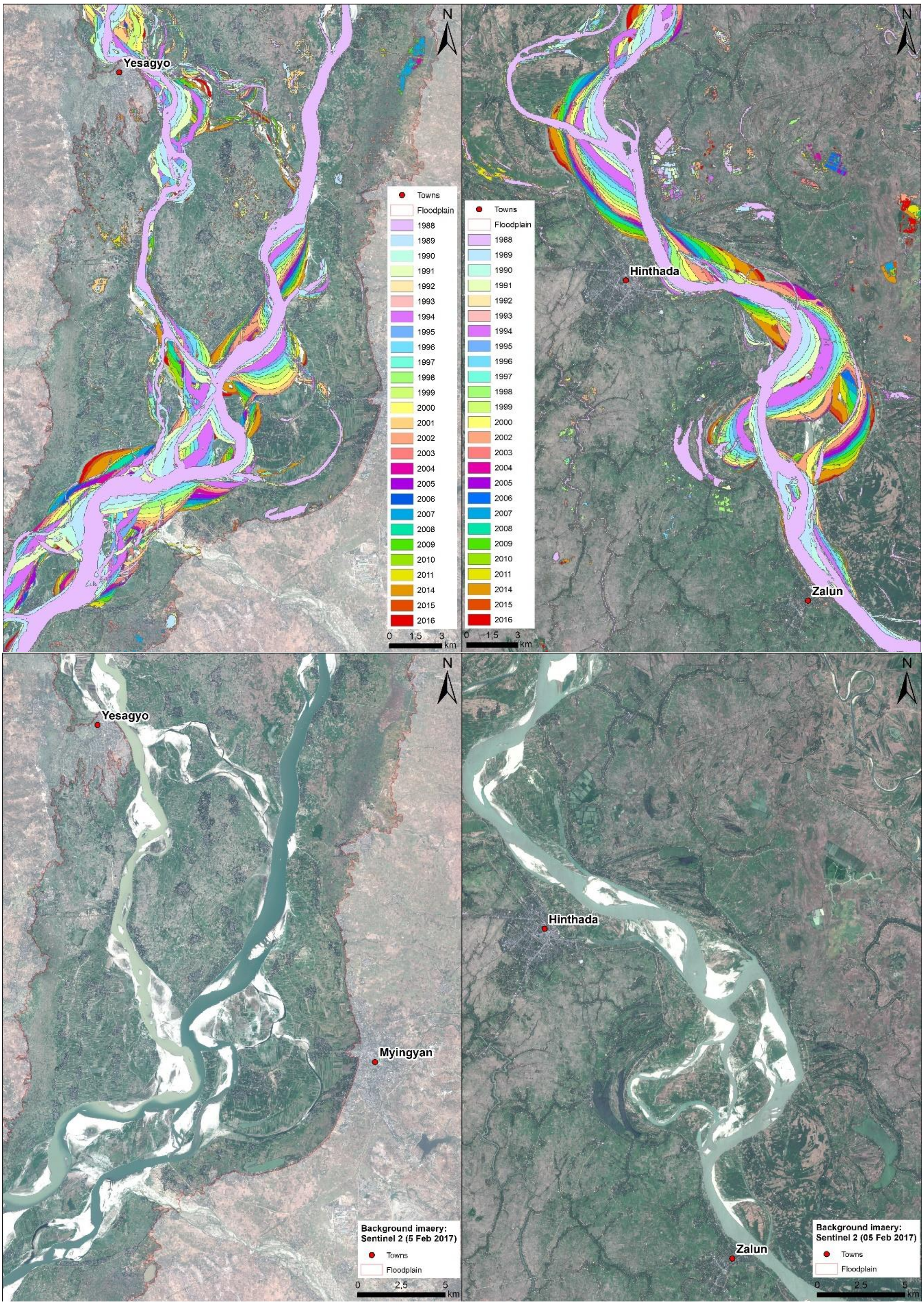


Figure 2.25). An analysis of satellite imagery from this region from 2006 to 2016 demonstrates that the

channel in this area has been active for at least the last decade (

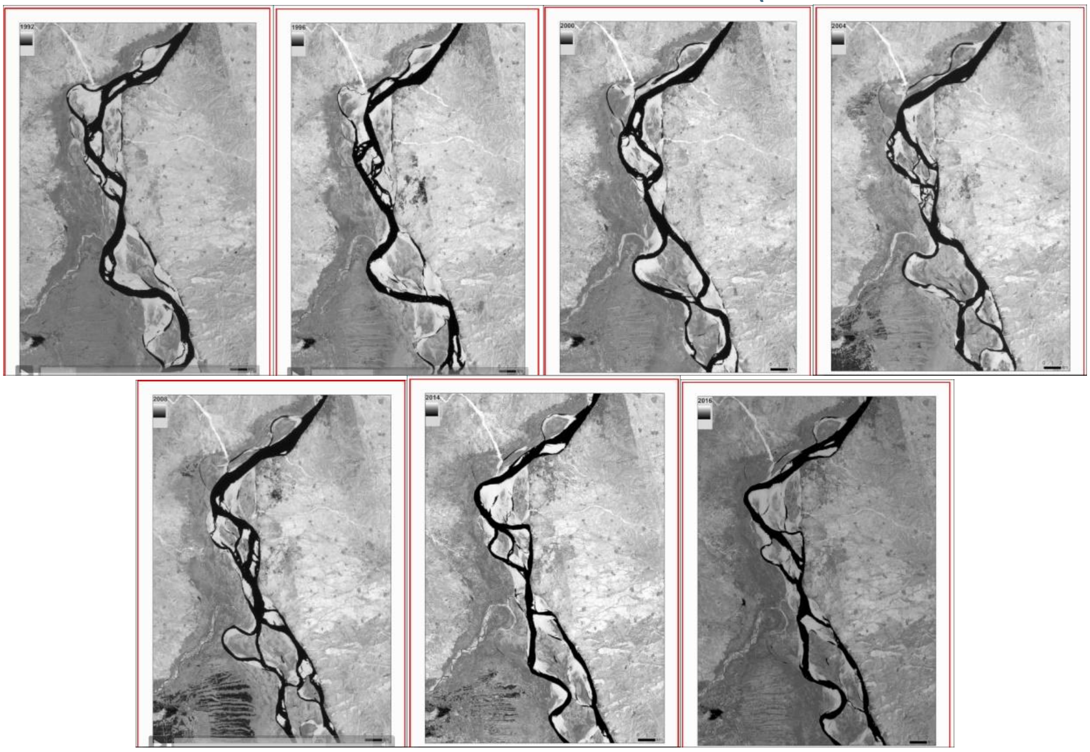


Figure 2.24).

Estimating rates of channel migration is not possible over long reaches of the river, because of the variability of changes over even short distances. Channel migration rates will be affected by flow rates, volumes of sediment input, the grain-size distribution of the sediment, and channel modifications such as changes to depth or bank modifications.

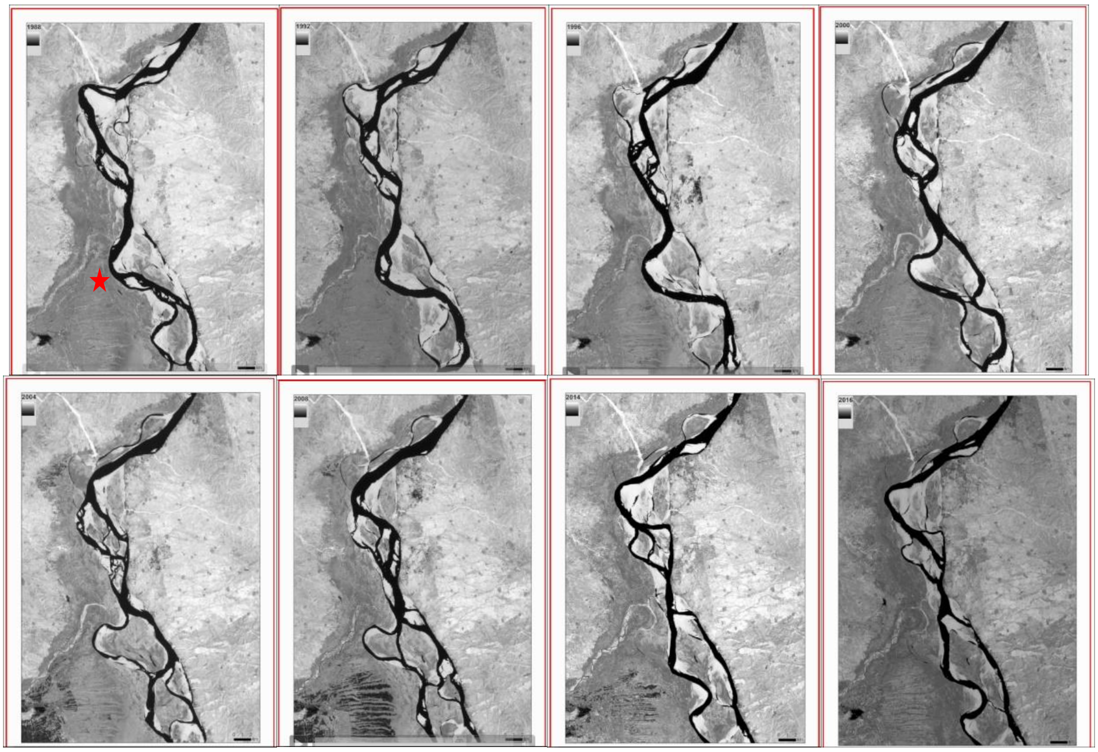


Figure 2.24 - Example of channel changes in the Ayeyarwady between Chauk and Yenangyaung. *Dates shown are 1988, 1992, 1996, 2000, 2004, 2008, 2014 and 2016*

.

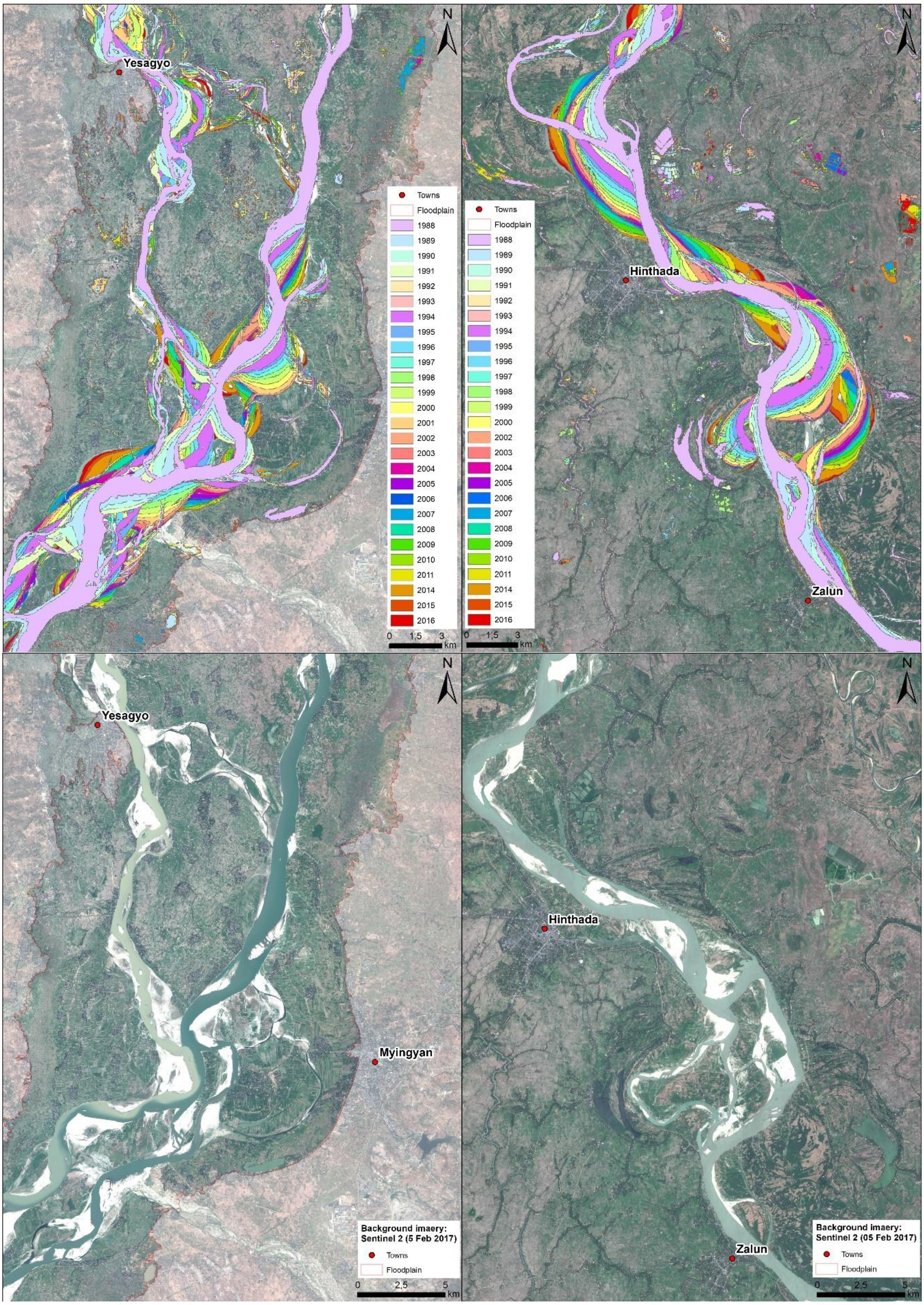


Figure 2.25 - (left) Channel migration at the confluence of the Chindwin and Ayeyarwady Rivers and (right) near the head of the delta near Hinthada. ***Annual changes to channels are shown in different colours 1988 - 2016. (bottom) 2017 images of the same river reaches***

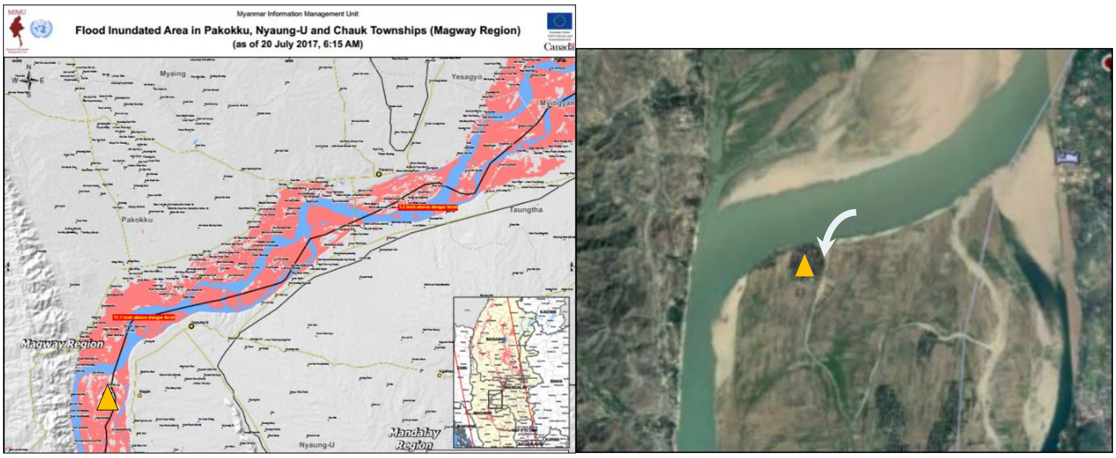


Figure 2.26 - (left) Map showing extent of flooding associated with abrupt channel changes in July 2017 that caused collapse of pagoda; (right) Google Earth image showing setting. Triangle near Magway shows location of recent channel changes and extensive bank erosion and arrow indicates area where channel was re-activated

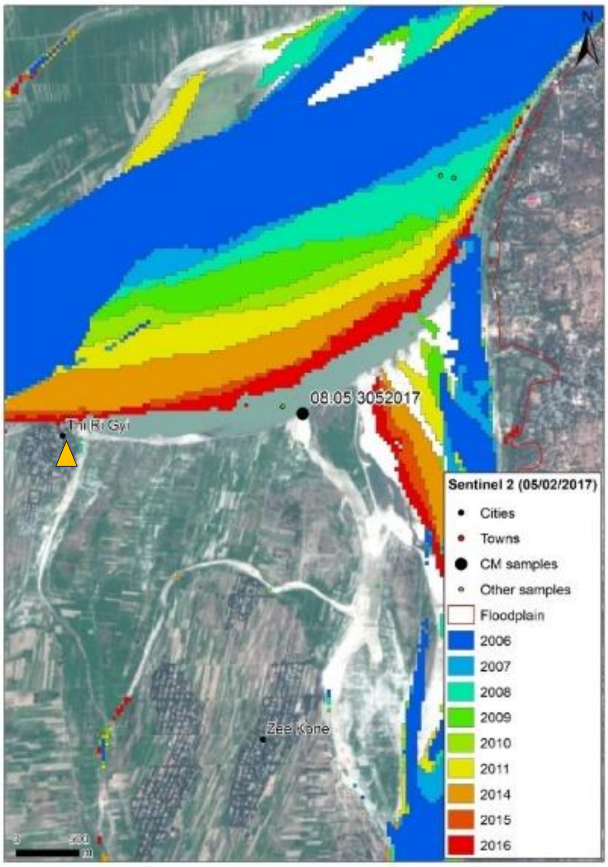
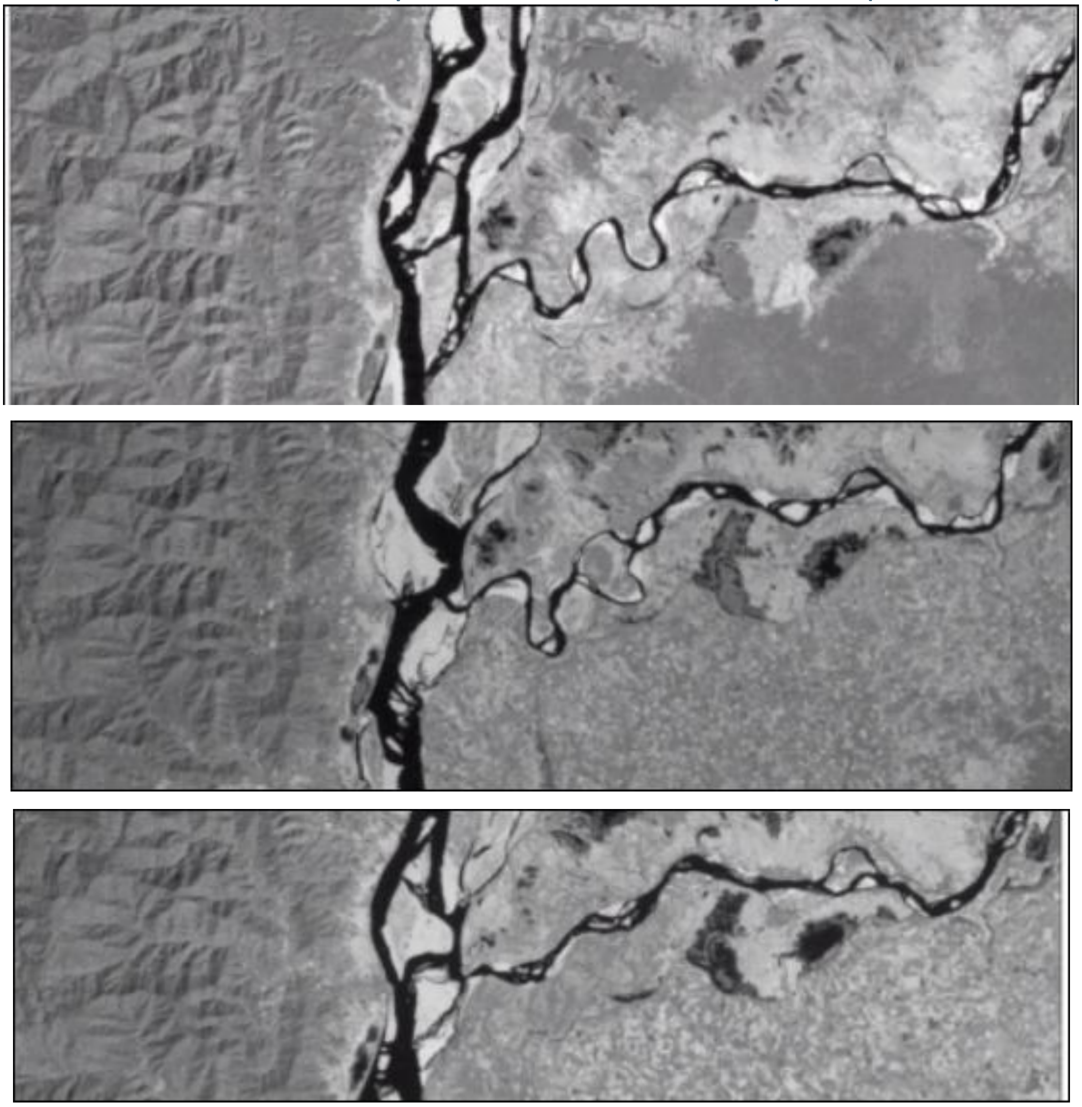


Figure 2.27 - Satellite image analysis between 2006 and 2016 of the migration of the river channel in the vicinity of the recent bank erosion

2.9 Sinuosity and Braiding Analysis

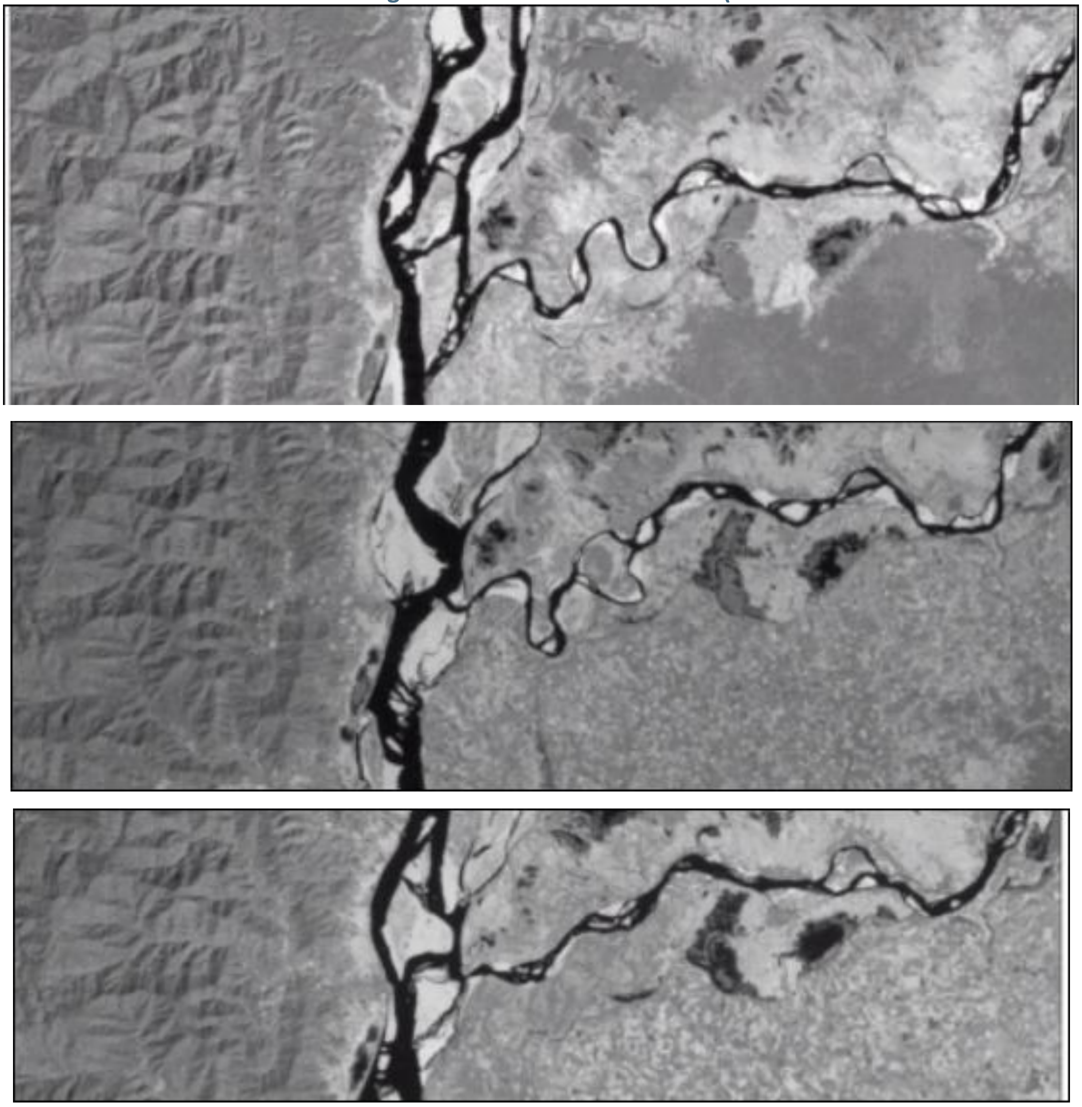
The planform (shape) of alluvial rivers is determined by a combination of the slope, sediment load and flow regime of the river. Meandering rivers tend to occur in sediment rich areas with low slopes, while braided rivers are more commonly associated with steeper areas with high levels of material transported as bedload. In the Ayeyarwady, channel form is also influenced by the presence of bedrock, with many of the alluvial reaches partly confined. Both meandering and braided river forms are recognized as being highly dynamic, so determining whether a channel is stable can be challenging. One approach to quantifying channel stability is the determination of channel form indices and tracking how these change over time. The stability of several alluvial reaches in the Ayeyarwady were investigated using two approaches:

The sinuosity of the lower Shweli and the alluvial reach in the Ayeyarwady located immediately downstream of the Shweli were quantified. Changes to the planform of the lower Shweli River are evident in aerial photos from the late 1980s to the present (



- Figure 2.28), and the investigation aimed to determine how changes in this major tributary may have affected the mainstream Ayeyarwady. Over the period ocaptured by the satellite images, from 1988 to 2016, the Shweli has undergone land use changes associated with deforestation, disturbance due to mining activities and experienced flow changes associated with the development of hydropower. The sinuosity analysis was completed by comparing the length of the main river channel to the centre line of the river (Roux et al., 2013). Values of 1 indicate a straight channel, values of up to 1.5 are considered sinuous and values >1.5 are considered meandering (Dey, 2014). Where a channel has multiple channels, the length of the primary channel is used for the analysis.

The braiding index of four alluvial reaches of the Ayeyarwady (zones G, J, K and L) was determined to understand how braiding patterns have changed over the past 30 years. Braided channel reaches are more common in the Ayeyarwady as compared to single channel sinuous reaches, so this analysis was considered appropriate. The braiding index is determined by comparing the length of the river valley to the combined length of all channels in the river (



- Figure 2.28).

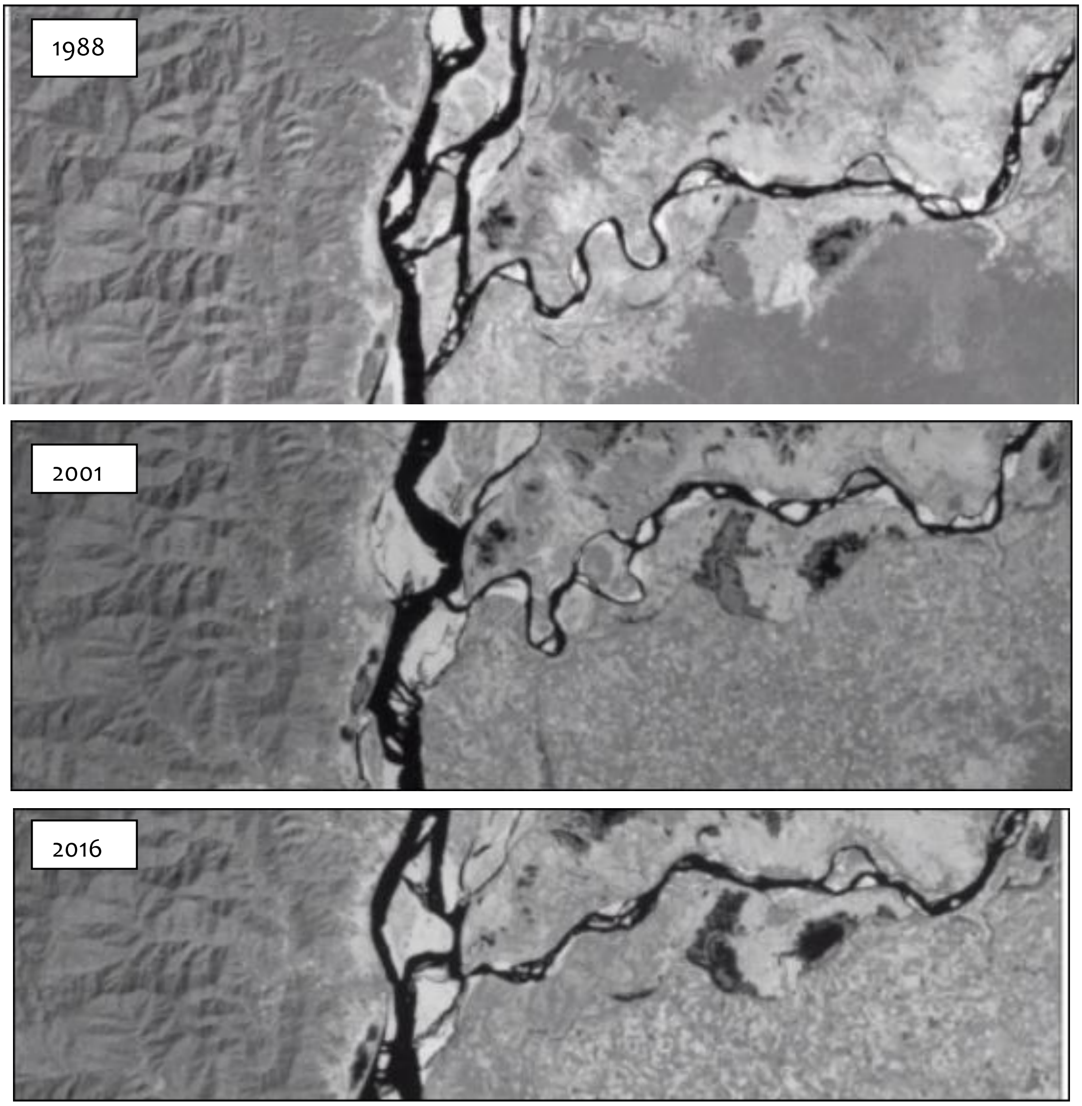


Figure 2.28 - Satellite images of the lower Shweli River showing planform changes between 1988 and 2016

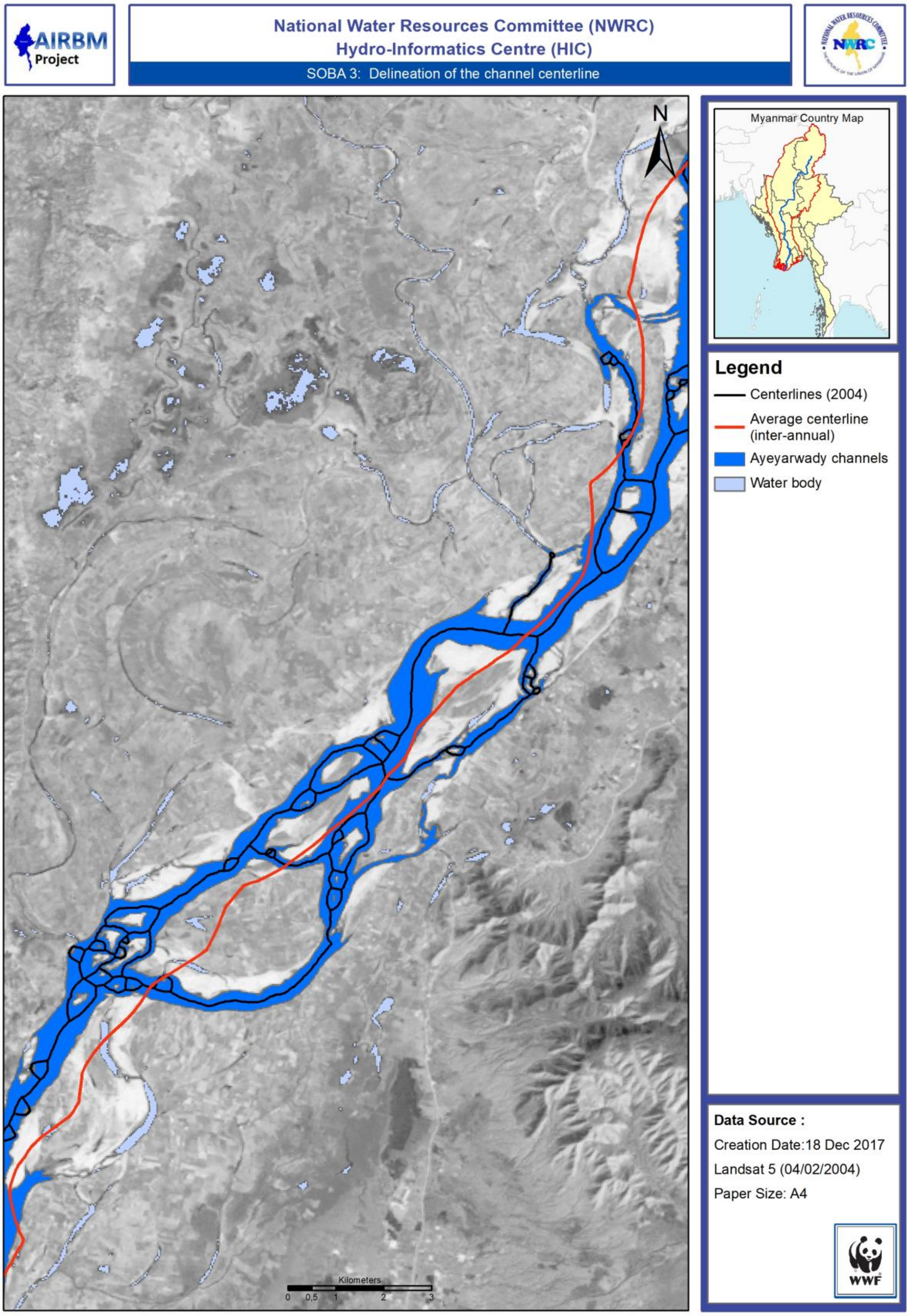


Figure 2.29 - Satellite image showing the centre line of the river (red) and the centre lines of the braided channels (black) used in the determination of the braiding index

2.9.1 Sinuosity

The sinuosity analysis for the Lower Shweli River and the Ayeyarwady downstream of the confluence (

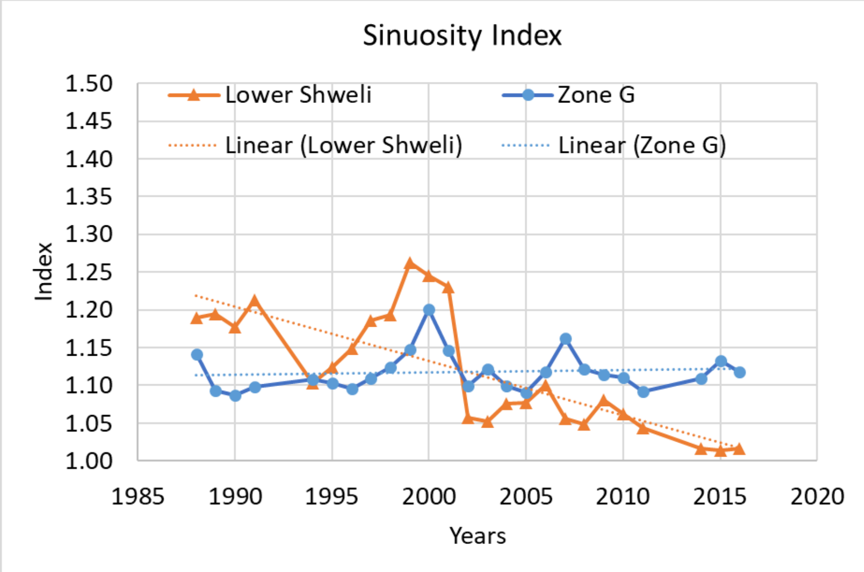
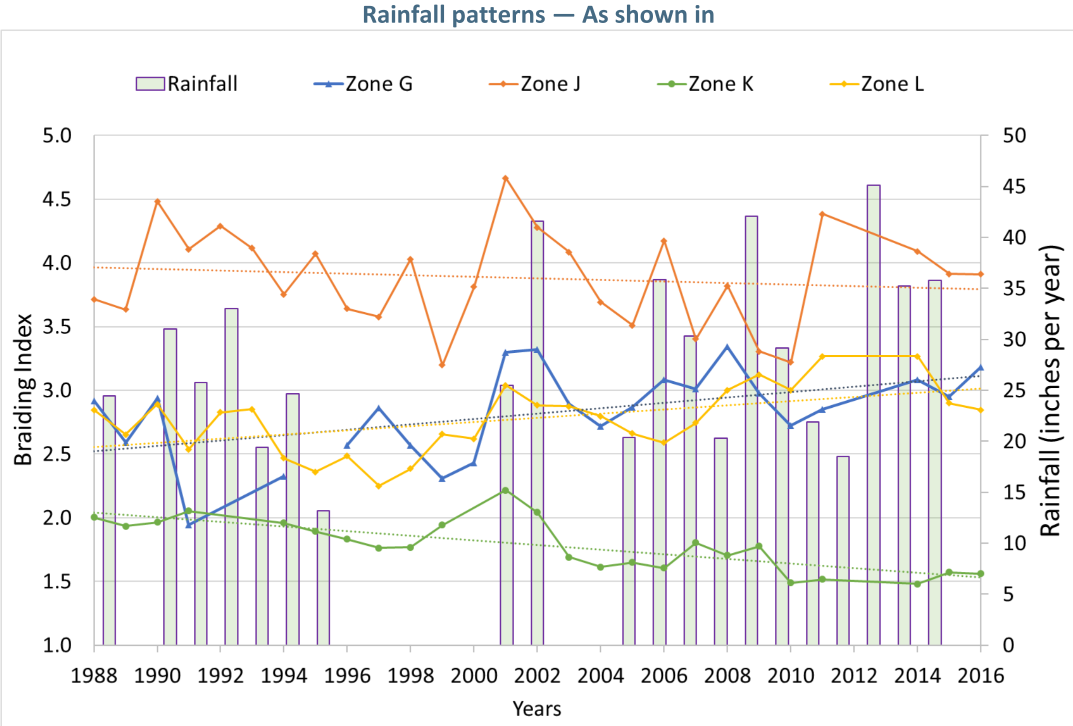


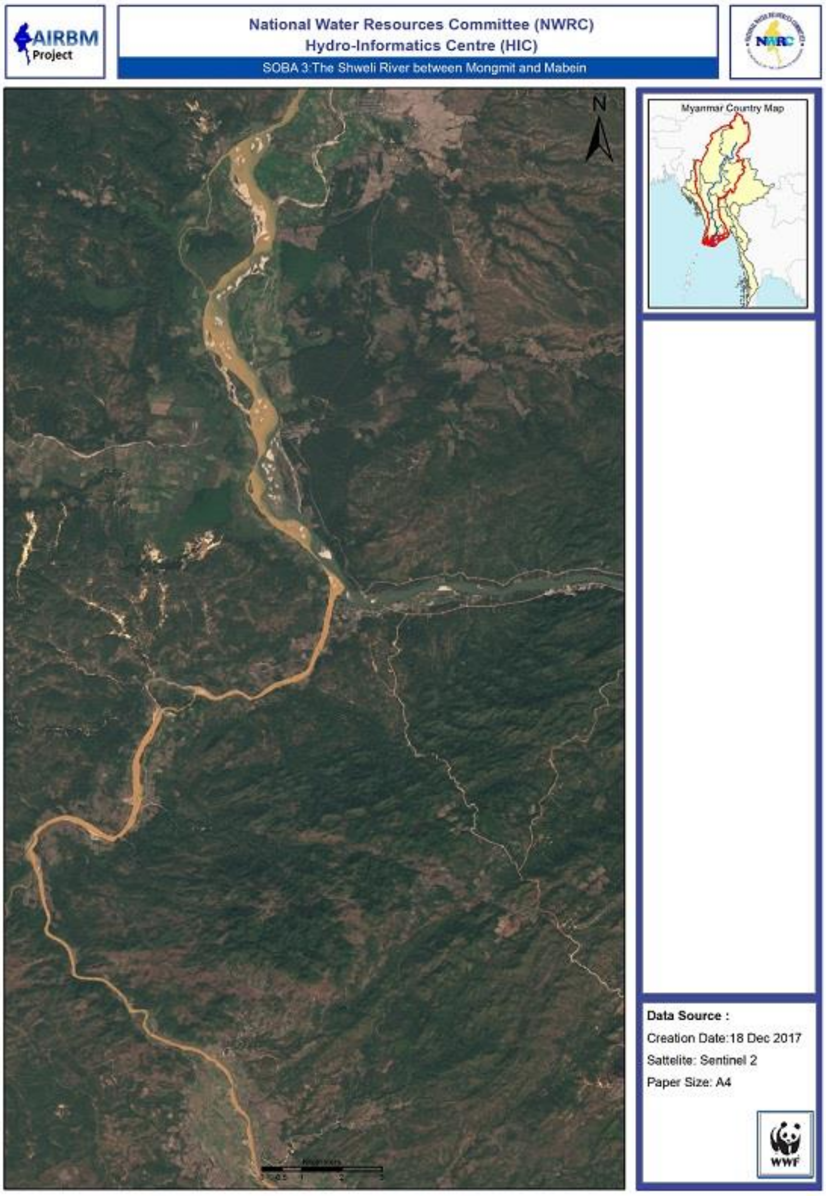
Figure 2.30) shows different trends for the two rivers. The Shweli was a sinuous river in 1988, but it has shown a strong decreasing trend ($R^2 = 0.6$) over the 30-year period, and is now virtually straight. Between 1988 and 2002, the river showed high variability in sinuosity, but no trend. The river experienced a large decrease in 2002 and then again showed variability but no trend until 2009. Since that time there has been a strong decreasing trend. There are several land use activities in the Shweli that have contributed to these changes, including:

Rainfall patterns — As shown in



- Figure 2.32, 2002 was a very wet year, and high rainfall and runoff could have driven the large decrease in sinuousity observed in the Shweli, due to the high river energy associated with elevated flows.

Land disturbance associated with mining — Mining is widespread in the Shweli catchment and disturbed areas can increase sediment input to the river (



- Figure 2.31). Increasing sediment loads in isolation are unlikely to decrease the sinuosity of the river, but can alter channel forms by decreasing river slopes or driving the river from a sinuous to a meandering or braided form.
- Hydropower development and flow regulation — Several dams exist on the Shweli upstream of the Myanmar border, and a large dam associated with the Shweli 1 hydropower project was closed in December 2006, with the hydropower plant becoming operational in 2008. Hydropower can affect the planform of rivers by altering the flow regime and reducing the sediment load. Altering the relationship of flow between the tributary and main stem can also affect channel form. For example, if the power station discharges seasonally high flows during the dry season when flow in the Ayeyarwady is low, the river energy in the lower river will increase due to the relatively low base level of the Ayeyarwady. These changes are consistent with the observed trends in the lower Shweli since 2009.

In contrast, the sinuosity results for the Ayeyarwady downstream of the Shweli show that it had a low sinuosity index in 1988, and although there has been variability, there is no overall trend. Both waterways show increases in sinuosity between 1995 and 2000, and decreases in 2001 and 2002, but since that time their results do not correlate. This reach is braided, so the sinuosity index may not be the best indicator of change. The braided index for this reach is discussed in the next section.

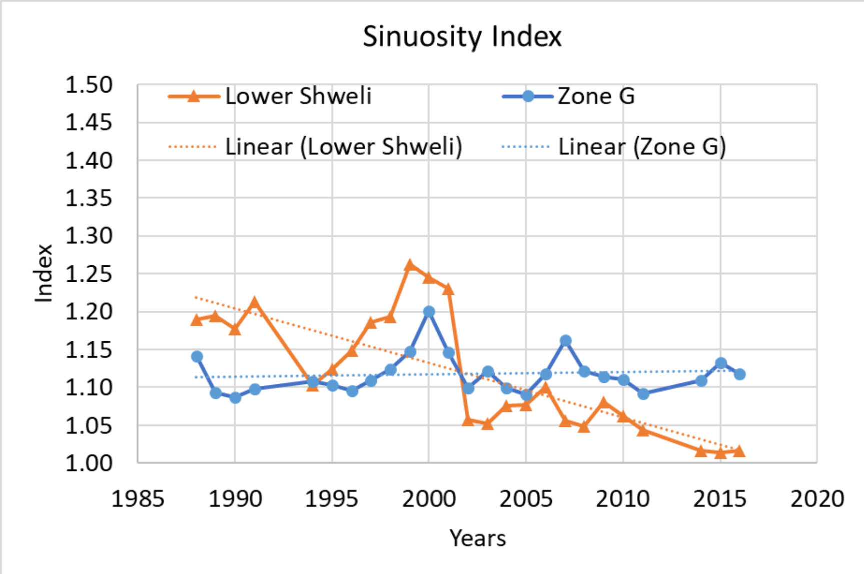


Figure 2.30 - Sinuosity index for the Lower Shweli River and the Ayeyarwady downstream of the Shweli (zone G)

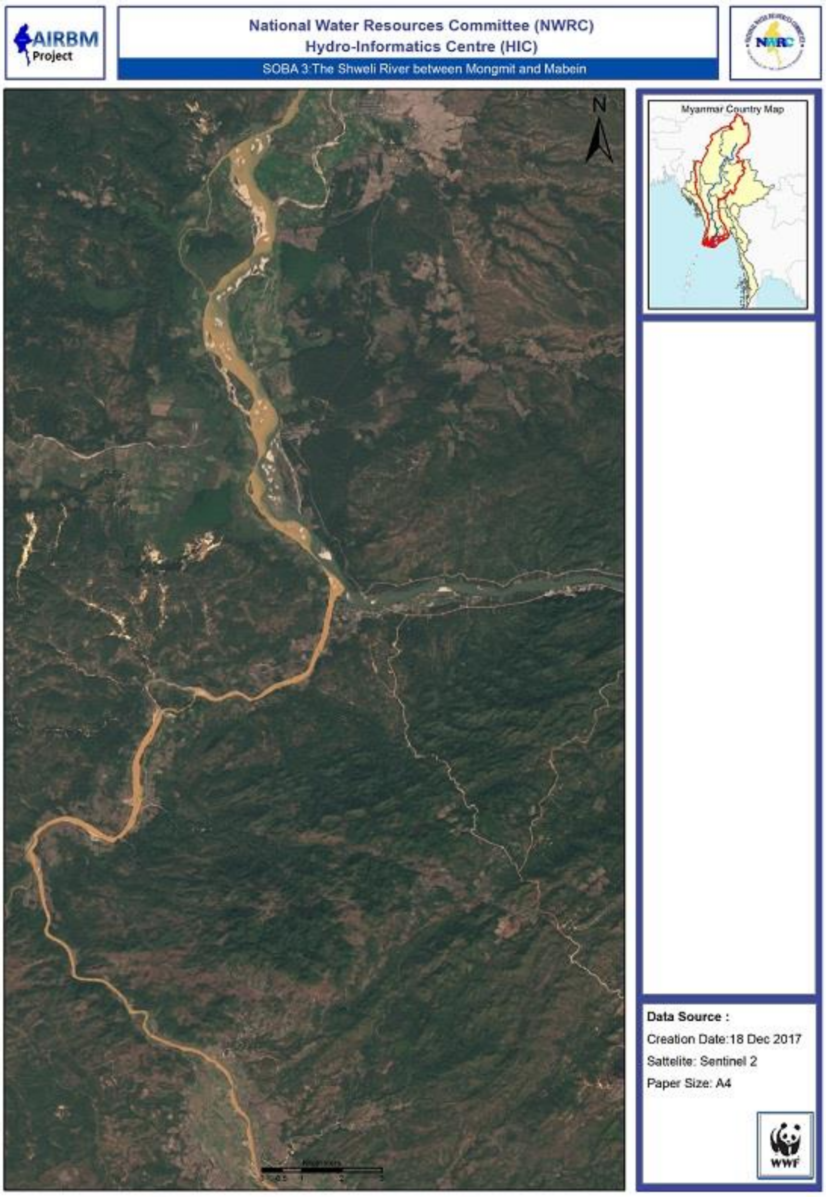


Figure 2.31 - Satellite image of Shweli River between Mongmit and Mabein showing high sediment input

2.9.2 Braiding Index

The results of the braiding index analysis for four geomorphic zones (G, J, K and part of L, see

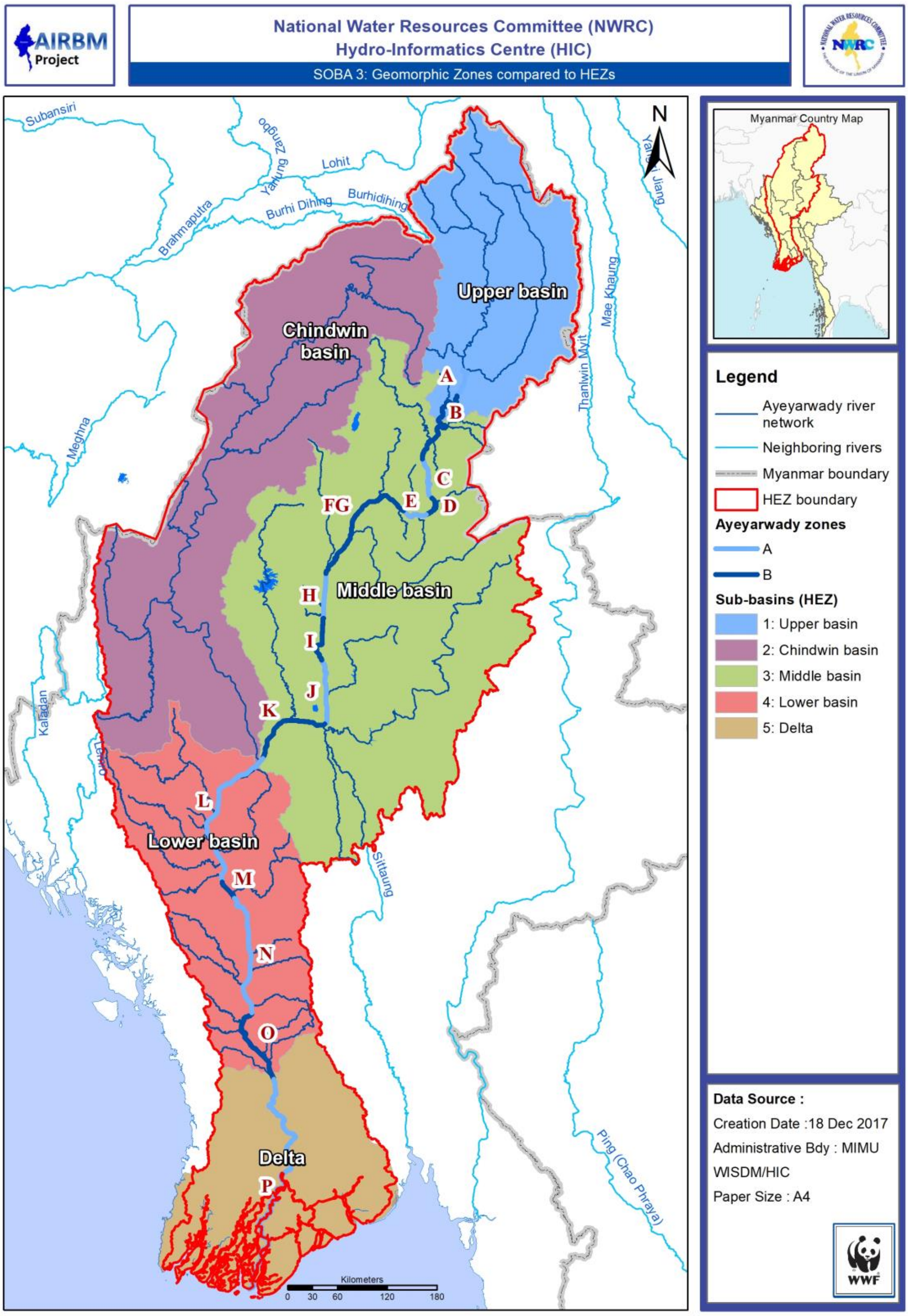


Figure 2.15) are shown in

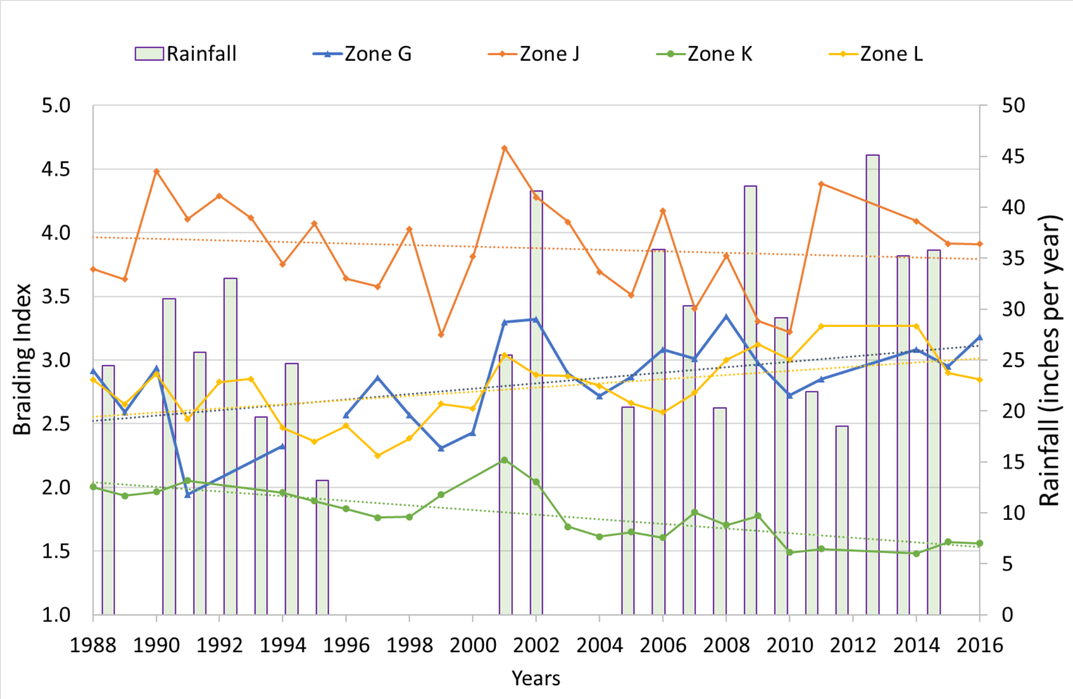


Figure 2.32. A comparison of the average of the index for each zone for the periods of 1988 to 1997, 1998 to 2007 and 2008 to 2016 is provided in

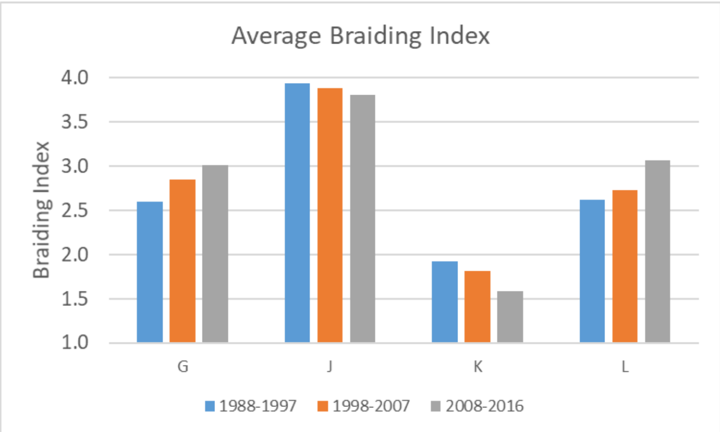


Figure 2.33. Of the four zones, K has the lowest slope (0.08) while G (0.12) and J (0.11) have the highest (see

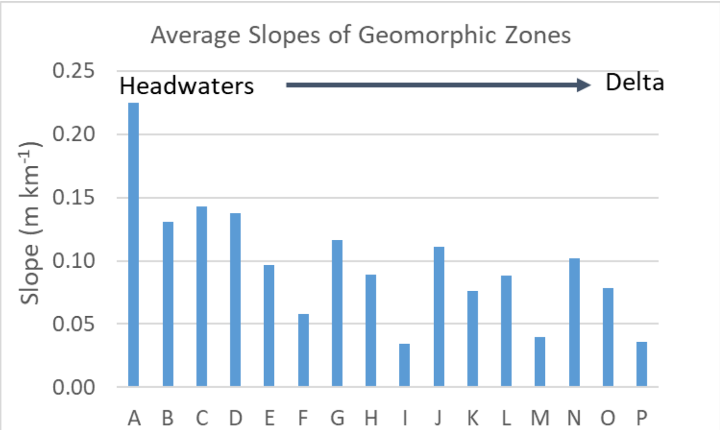


Figure 2.20).

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The braiding index for the most upstream zone, G, shows an increasing trend, with most of the increase occurring before 2008. This increase is reflected in the average results, which show an increase between each period (

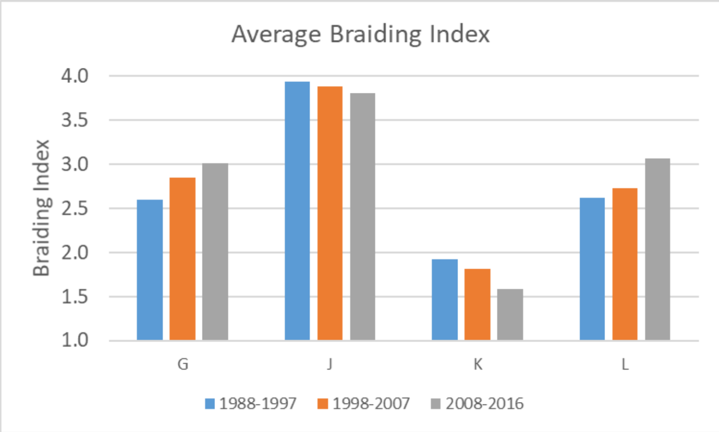


Figure 2.33). The sinuosity index showed a peak in 2000, and the braiding index increased over the following years as the sinuosity decreased, suggesting the adjustment of the channel to increasing sediment loads. Lower variability since 2008 might be related to flow regulation in the Shweli and other rivers in the upper Ayeyarwady reducing sediment input, as discussed in the previous section.

Zone J exhibits the highest overall degree of braiding, with indices ranging from 3.2 to 4.6. There is a very weak decreasing trend in the 30-year dataset, and the averaged results show small decreases over each of the periods. The results suggest a repeating pattern of decreasing braiding punctuated by rapid increases at intervals of about 10 years, that coincide with low rainfall. This may reflect the river increasing braiding due to the lower water flows being unable to transport the high sediment loads. This reach is also adjusting to the development of the hydropower in the upper Ayeyarwady and the Sedawgyi hydropower project that regulates the inflow of the Ma Gyi Chaung that flows directly into this zone, which became operational around 1989.

Zone K, located just downstream from J, exhibits very different behavior, having the lowest range of braiding index of any of the reaches. Between 1988 and 2010, the index decreased from 2 to almost 1.5, and has shown little change since then. In addition to adjusting to the flow alterations in the upper Ayeyarwady, local flow and sediment inputs have been altered by development of the Thapanzeik multi-use hydropower and irrigation scheme in the Mu River in 2002, four hydro schemes in the Zawgyi/Myogi catchment that have come on line between 1990 and 2015, and the large Yeywa hydropower project on the Myitnge that was commissioned in 2010. Collectively, these flow alterations may be reducing high flows and the ability of the river to braid, confining flow to a single channel. The averaged results over the three periods show a continual decrease.

The most downstream zone investigated, zone L is situated downstream of the confluence with the Chindwin River. The zone from the confluence of the Chindwin to Chaulk was excluded from the analysis because of the influence of bedrock on the structure of the river near Old Bagan. This reach shows a similar range of braiding as zone G, and a similar increase in average values (

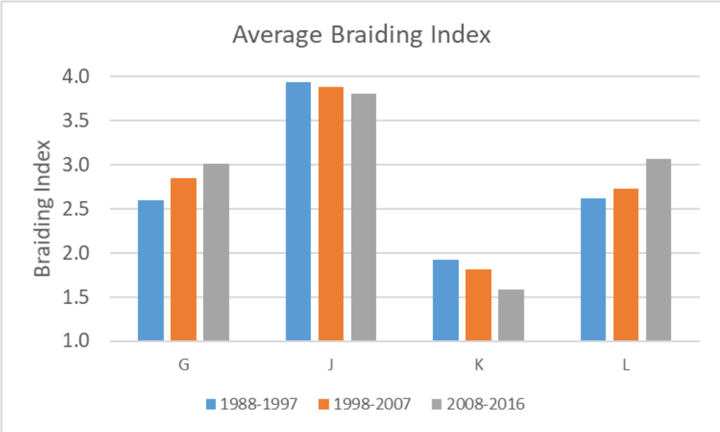


Figure 2.33). Although the starting and ending braiding values are similar, the first part of the record shows lower values as compared to the second half.

Given the complexities of processes controlling river planform, and the lack of available information related to the flow and sediment regimes of the river, it is difficult to interpret the braiding results. However, a possible large-scale explanation for the observed changes over time and downstream may be that zones G and L are responding to increased sediment loads under relatively natural flow regimes due to G being close to the headwaters, and L being downstream of the Chindwin which has a very low level of development. These zones show low rates of increased braiding, which could also reflect changing rainfall patterns. The other two zones, J and K are located within the most developed area of the Ayeyarwady with respect to large-scale dams, and show decreased rates of braiding. Zone J, which is steeper, shows lower rates of change, possibly due to the high sediment loads that continue to enter from the mining affected areas upstream. Zone K, which has the lowest slope and highest flow regulation, may be showing the greatest response to flow and sediment changes.

This analysis highlights that different parts of the river can respond differently to the same catchment conditions, and a site-specific understanding of the river on a reach-by-reach basis is required for management. Piegay et al., (2006) identified a range of potential management strategies related to managing braided rivers, including approaches for both increasing and decreasing braiding. However, the authors concluded that management strategies need to be identified within the context of 1) where the river is with respect to its trajectory of geomorphological evolution, 2) existing or potential ecological values or benefits, and 3) human requirements for safety and protection of economic interests. These guiding principles suggest that an integrated understanding of the geomorphological, ecological, social and economic values of river reaches need to be developed before appropriate management strategies can be identified or implemented.

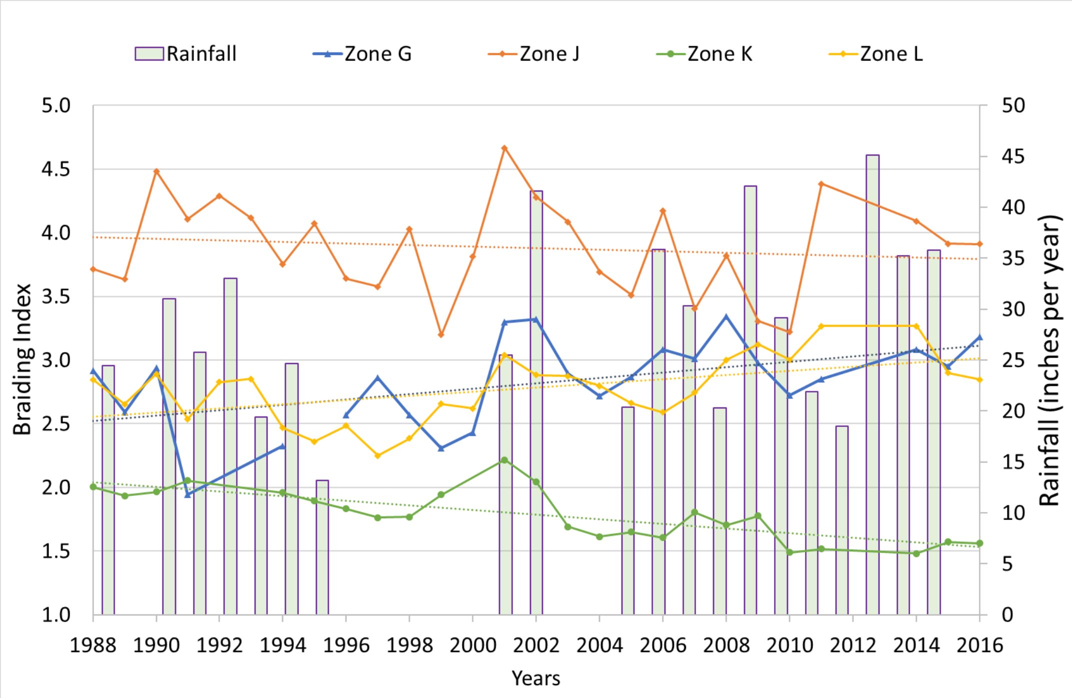


Figure 2.32 - Braiding index for four geomorphic zones in the Ayeyarwady between 1988 and 2016 ***Rainfall totals for Kin Oo Sagaing shown on right axis***

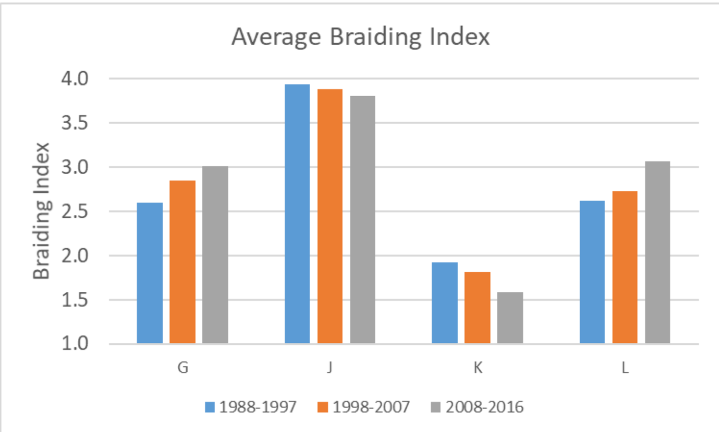


Figure 2.33 - Average braiding index for reaches in the Ayeyarwady for the periods 1988 to 1997, 1998 to 2007, and 2008 to 2016. ***X-axis denotes geomorphic zones***

3. CATCHMENT ACTIVITIES AFFECTING THE GEOMORPHOLOGY OF AYEYARWADY RIVER

Land and river use can affect the geomorphology and sediment transport in a river through altering: the quantity of sediments available for transport, by either increasing or decreasing availability; the landscape, such that water and sediment pathways are changed; the quantity of water available for runoff; or the timing of water flow in the river.

Four activities which affect sediment transport and geomorphology in rivers include: deforestation and changes to vegetation, including agriculture; terrestrial based mining; hydropower development; and sand and gravel mining from rivers. Each of these activities has been investigated by SOBA 3. Changes to vegetation patterns were investigated through a literature review and analysis of satellite imagery; land areas disturbed by terrestrial mining were quantified using satellite imagery from 1987 to the present; information about hydropower development was obtained from a recent Strategic Environmental Assessment project of the Hydropower Sector in Myanmar (IFC et al., 2017); and sand and aggregate mining in the Ayeyarwady was investigated through a survey implemented by the SOBA 3 Team. The results of these activities are summarised in the following sections.

3.1 Deforestation

Deforestation affects rivers by increasing the availability of sediment and altering rainwater runoff. The removal of vegetation from landscapes increases the susceptibility of the underlying soils to physical erosion through exposure to direct raindrop attack, runoff, or wind. Increased sediment input to rivers can alter the channel morphology by choking channels, elevating the bed level and/or changing the slope of the local channel. Increased sedimentation can alter habitat distribution and condition, by coating substrates or infilling gravel beds with fine material. The increased runoff of fine-grained material can increase the turbidity of rivers, reducing the viability of aquatic vegetation and ecological communities.

Deforestation can also alter the hydrologic balance within catchments as evapotranspiration is reduced, altering soil moisture properties and the potential for physical erosion and runoff. Deforestation has been linked to the alteration of micro-climates by changing temperature regimes up to several degrees on a seasonal basis (Li et al., 2015). Removal of vegetation from riparian zones increases the susceptibility of the bank face to erosion. The destabilization of banks and hillslopes through deforestation can increase the occurrence of episodic sediment input events such as land slips, owing to a reduction in stability provided by the root systems of plants.

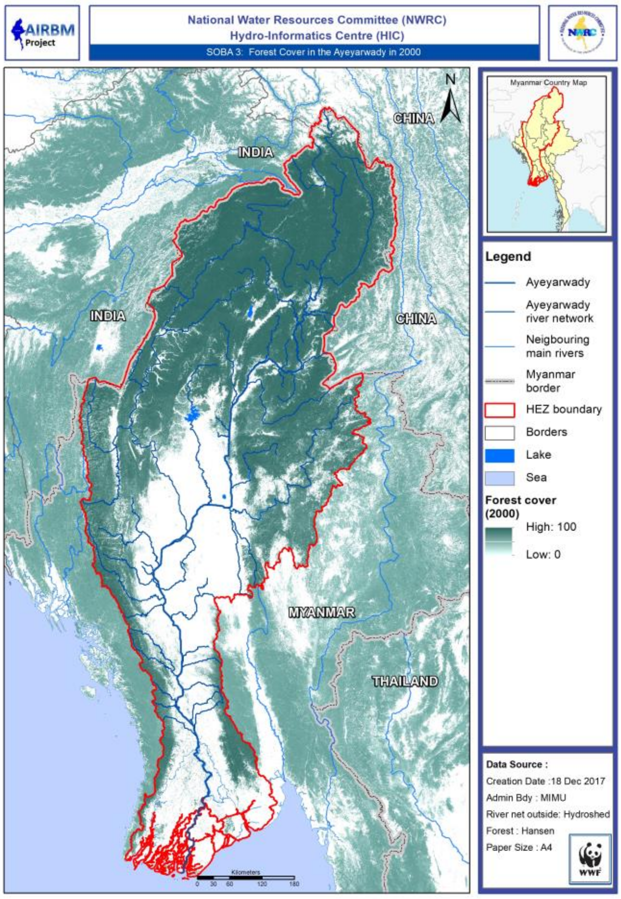
Myanmar is one of the most extensively forested countries in mainland Southeast Asia, and has been recognized for its teak reserves and expensive forests (Bryant, 1997; Leimgruber et al., 2005) extending from the lowlands of the Ayeyarwady Delta to the hilly regions and alpine forests of the Himalayas (Leimgruber et al., 2005). However, according to the United Nation's Forest and Agriculture Organization (FAO, 2010), Myanmar lost an average of 465,388 hectares (ha), or 1.2% of its total forest cover each year between 1990 and 2010, totaling a loss of 7,446,215 ha or 20% over the period (Woods, 2015). A recent report warns that up to one-third of the country's remaining natural forests could be lost within the next two decades if the current rates of deforestation are maintained (WWF, 2013). The following analysis considered deforestation over two separate periods: prior to 2000, and 2001 to 2014.

3.1.1 Deforestation prior to 2000

Deforestation has a long history in the Ayeyarwady River basin, as most of the swamp, mangrove and dense lowland evergreen forests were cleared by human settlement by the late 19th century (Bryant, 1997; Leimgruber et al., 2005).

Between 1990 and 2000, forest cover changes varied considerably across the country. Annual clearing rates were the highest in the Ayeyarwady, Mandalay and Sagaing divisions, ranging from 0.4% to 1.2% (Leimgruber et al., 2005). Two deforestation hotspots experienced unprecedented levels of forest cover change. One was the delta region that lost about 12% of its remaining forest cover in only 10 years (FAO, 2001). It is estimated that more than 20% of the mangrove forests were lost due to fuelwood collection, particularly where pristine delta forests stretched across the Ayeyarwady and Yangon Division (FAO, 2001). The second area that experienced a high rate of deforestation was on the northern edge of the Central Dry Zone and in the Ayeyarwady Valley, where 7% of the land had been degraded or converted to other uses. The continuous human encroachments, including widespread and unplanned agricultural expansion, have caused these major forest losses.

Forest cover based on the distribution of vegetation exceeding 5 m and forest density in 2000 (



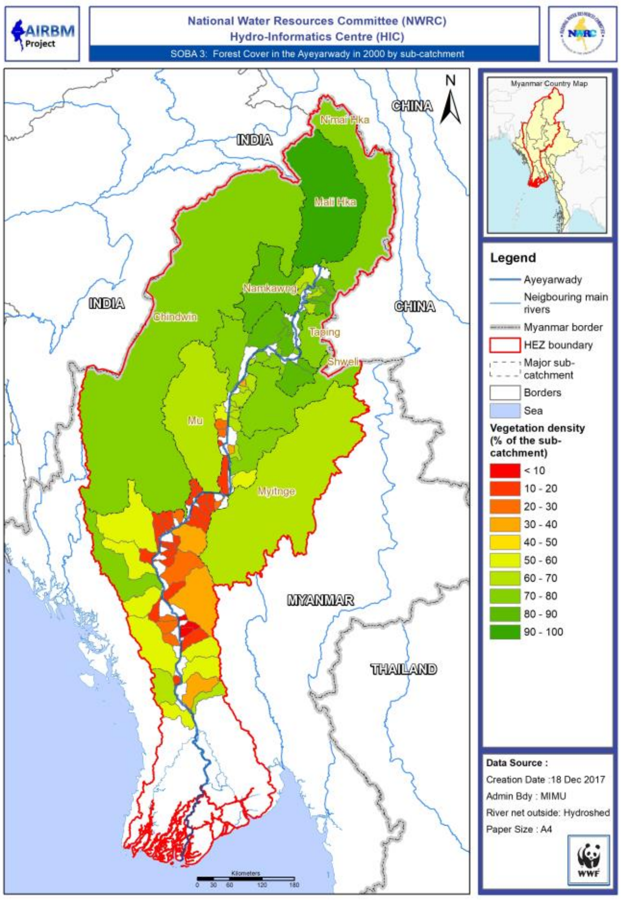


Figure 3.1) reflects these changes with vegetation cover concentrated in the upper Ayeyarwady and Chindwin basins, and low levels of cover in the Central Dry Zone and the delta (Hansen et al., 2013). The small sub-catchments that drain directly to the main stem of the Ayeyarwady, particularly those in the central region, exhibit very sparse vegetation cover because of the significant impact of agriculture and the dry climate, which impedes rapid regeneration of the degraded vegetation. Sparse vegetation cover in these catchments can promote increased sediment discharge to the river, due to the lack of cover on the land. Removal of riparian vegetation will also increase the risk of bank erosion and channel changes due to the lack of bank protection. Vegetation physically protects the underlying bank, and increases the roughness of the bank, which leads to a reduction in shear stress of the flowing water in contact with the bank face.

Of the larger catchments, the Yaw, Mu and Myitnge Rivers showed the lowest rates of forest cover in the Ayeyarwady in 2000. This reduced vegetation cover is likely to have increased sediment supply to the Ayeyarwady, especially in the steep Myitnge headwaters, and in the dry Yaw catchment. The lack of vegetation may also have increased runoff from the sub-catchment.

3.1.2 Deforestation from 2000 to 2014

The rate of forest cover between 2000 and 2014 was estimated based on the Global Forest Watch database and the work of Hansen et al., (2013).

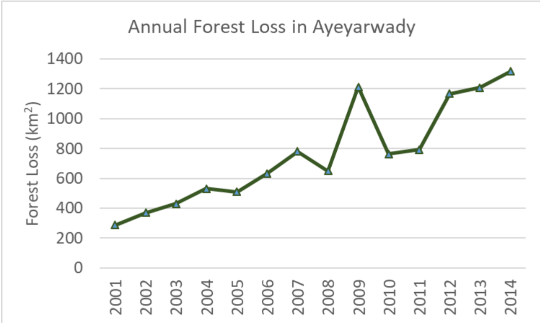


Figure 3.2 shows the annual rate (in square kilometres per year [km^2yr^{-1}]) of deforestation in the Ayeyarwady catchment, and clearly shows an increasing trend in the loss of forest cover. The area deforested in 2014 was estimated at over four times that measured in 2000.

Much of this deforestation was driven by the growth of rubber plantations that were promoted by the central government, with a goal of 465,388 ha planted between by 2030. These plantations are predominantly located in the northern (Kachin state) and eastern (Shan state) areas of the watershed.

During the 2000 to 2014 period, a significant amount of deforestation not only occurred in the small sub-catchments along the Ayeyarwady River (Namkwi Hka, Teinkyi, Wein, Yebyu and Baw) but also in higher order sub-catchments like the Nam Tabet, Shweli and Taping, situated to the east, between the territories of Myanmar and China (

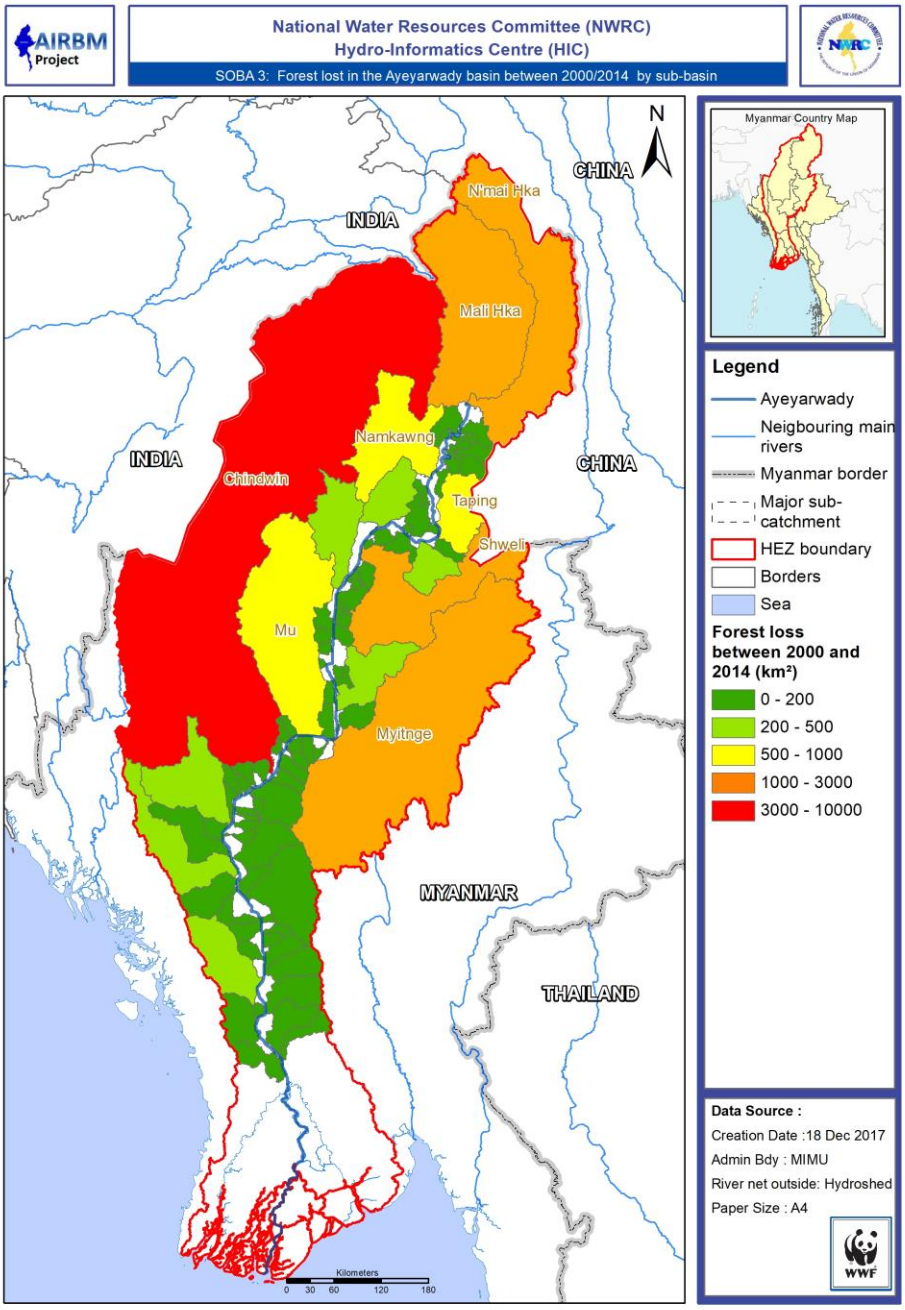


Figure 3.3). The lower rates of deforestation in many of the central and downstream areas are because of the relative scarcity of forests in 2000 due to historical depletion in those densely populated areas, which was discussed in the previous section.

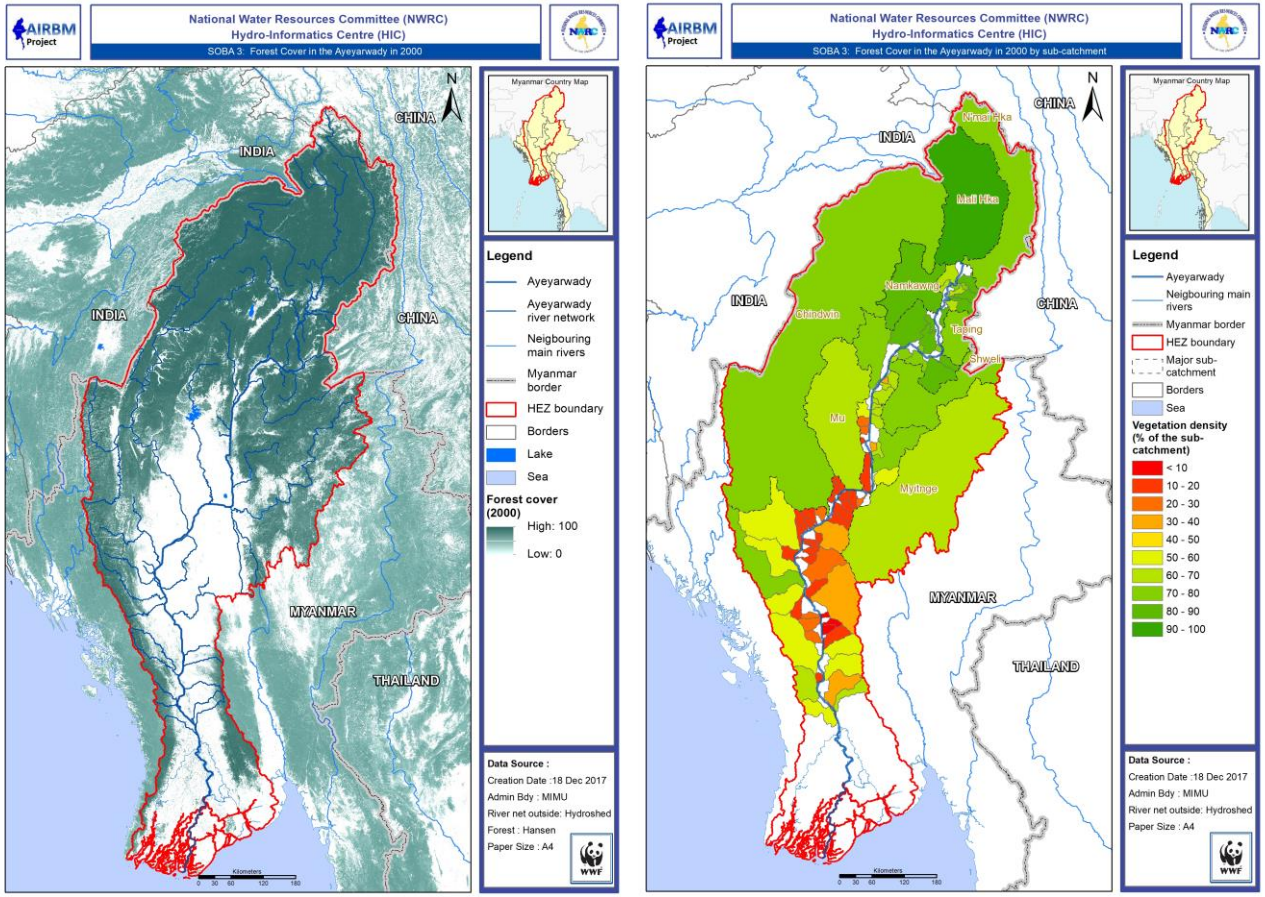


Figure 3.1 - (left) Percent of forest cover by vegetation greater than 5 m and (right) forest density by sub-catchment in 2000. ***(Data from Global Forest Watch. Based on Hansen et al., 2013) and (right) forest density grouped by sub-catchment, based on the same data.***

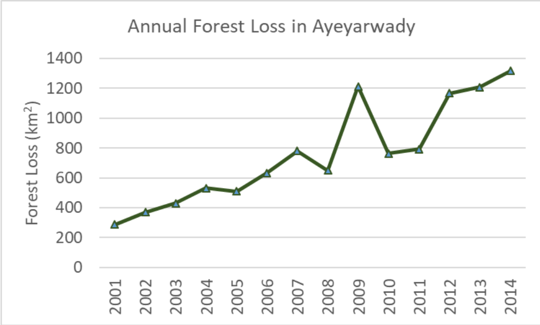


Figure 3.2 - (left) Annual forest loss in the Ayeyarwady watershed between 2000 and 2014 *(Hansen et al., 2013)*

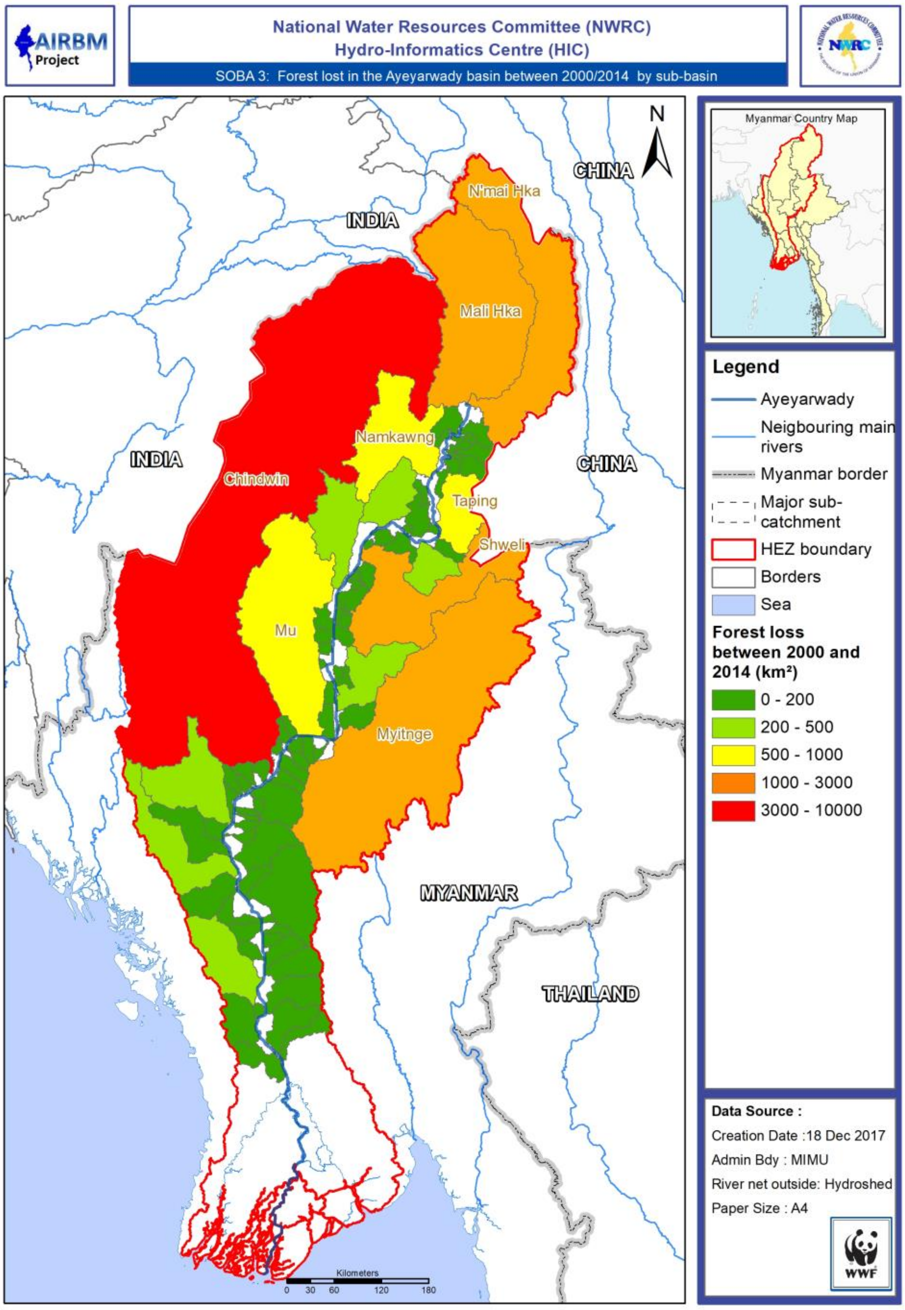
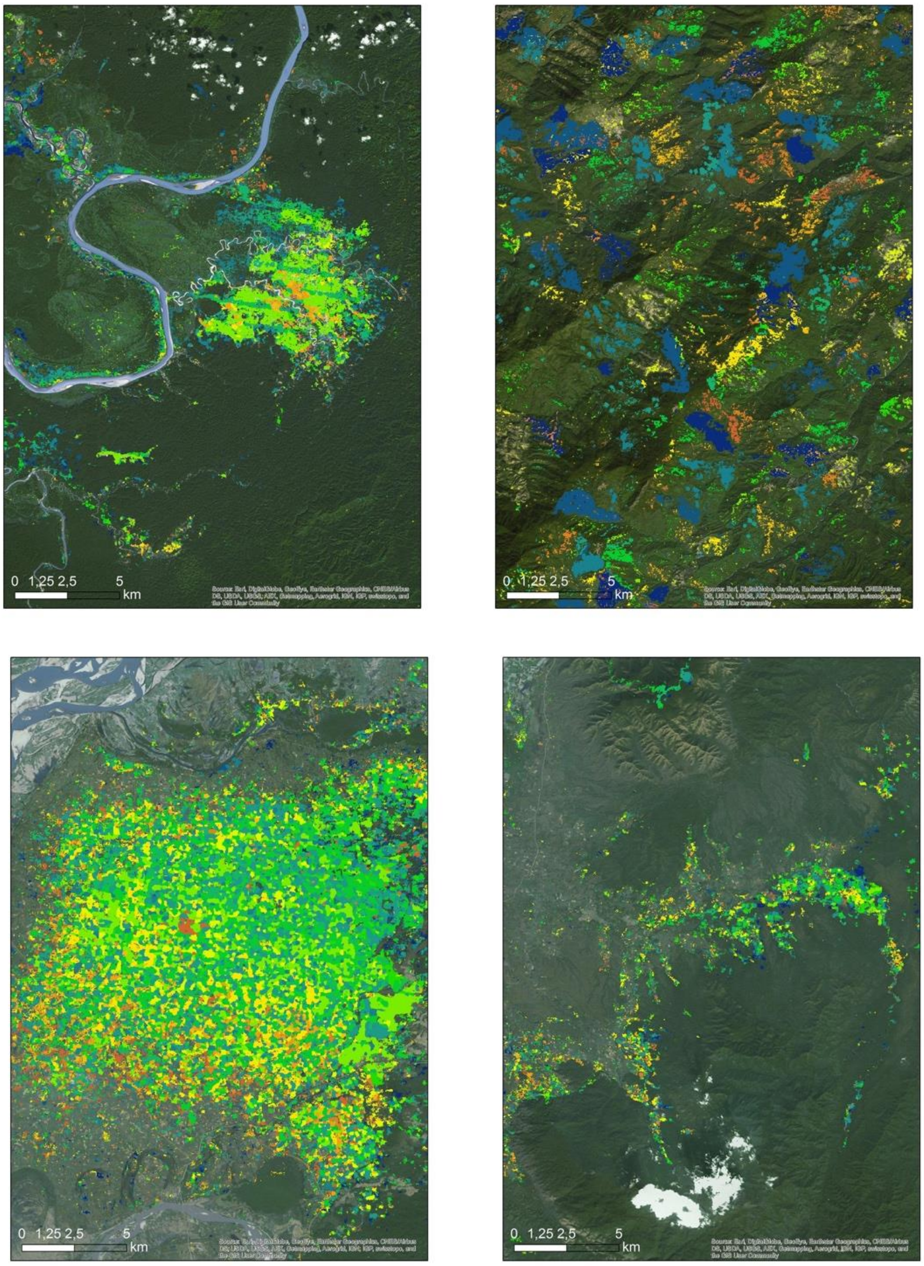


Figure 3.3 - Total forest loss (km²) by watershed, between 2000 and 2014

Deforestation occurs in different patterns depending on the activity driving the land change. Examples of deforestation linked to terrestrial mining, shifting agriculture, and the expansion of agriculture in different regions of the Ayeyarwady are shown in



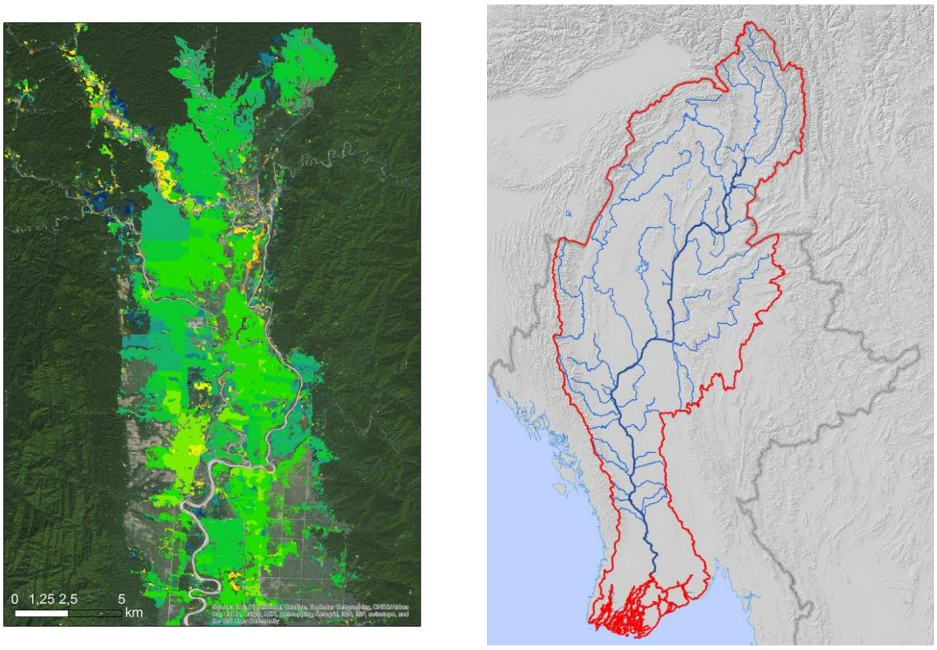


Figure 3.4 - Deforestation patterns in the Ayeyarwady watershed.

Photo 1: caused by mining along rivers (Chindwin valley); Photo 2: patchy distribution of deforestation and regeneration, typical of widespread shifting cultivation; Photo 3: progressive replacement by cultivation on floodplain; Photo 4: agricultural colonization front encroaching up hillslopes from a valley; Photo 5: conversion of lowland forest to rubber or other plantations. Locations shown in map (6) (Raw data from Global Forest Watch).

. These patterns will affect how land use changes alter river processes. Areas on hill slopes that are cleared on a large scale have the potential to increase water and sediment runoff to rivers, whereas agriculture developed on floodplains potentially has little impact on sediment delivery to the river, but may increase bank erosion if riparian vegetation is removed.

An example of high levels of sediment input from deforested areas is shown in

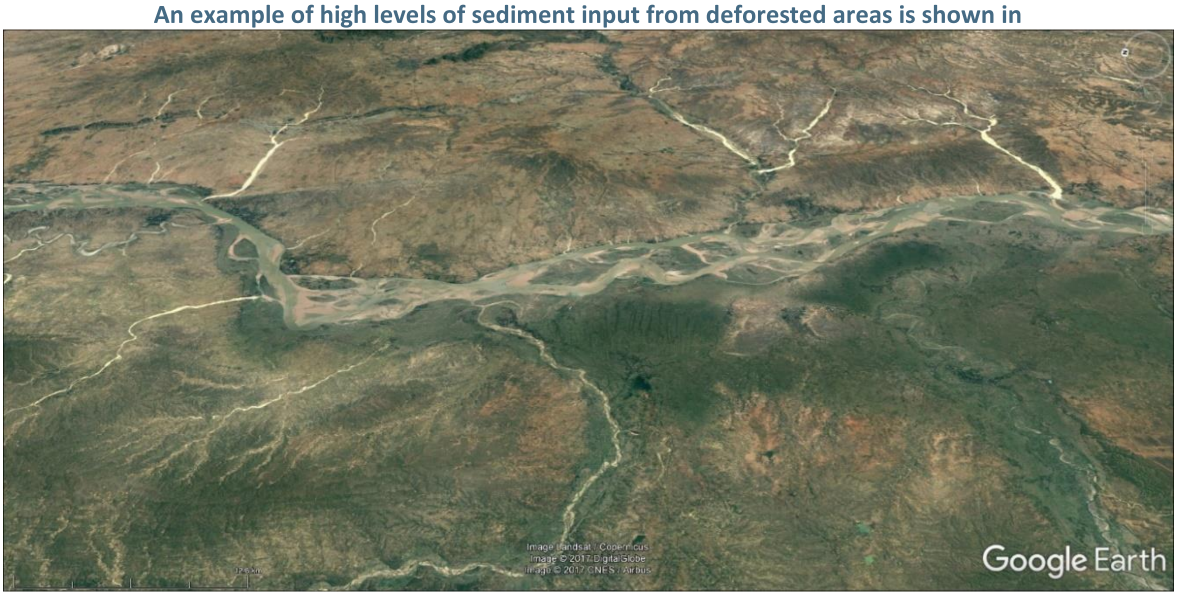
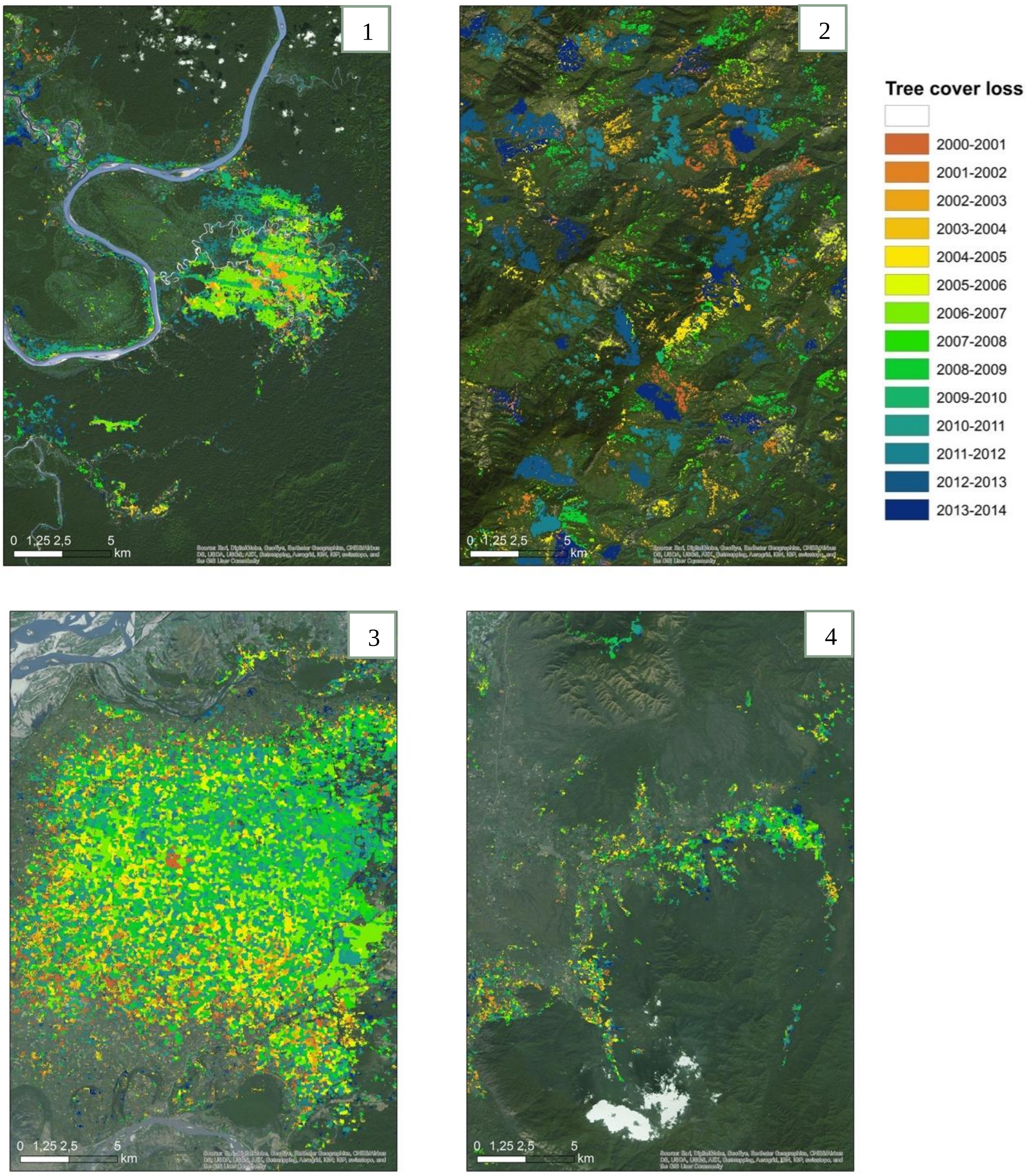


Figure 3.5, where tributaries in the Central Dry Zone carry elevated sediment loads from catchments with extensive deforestation.


1
2
3
4
Tree cover loss
2000-2001
2001-2002
2002-2003
2003-2004
2004-2005
2005-2006
2006-2007
2007-2008
2008-2009
2009-2010
2010-2011
2011-2012
2012-2013
2013-2014
0 1,25 2,5 5
km

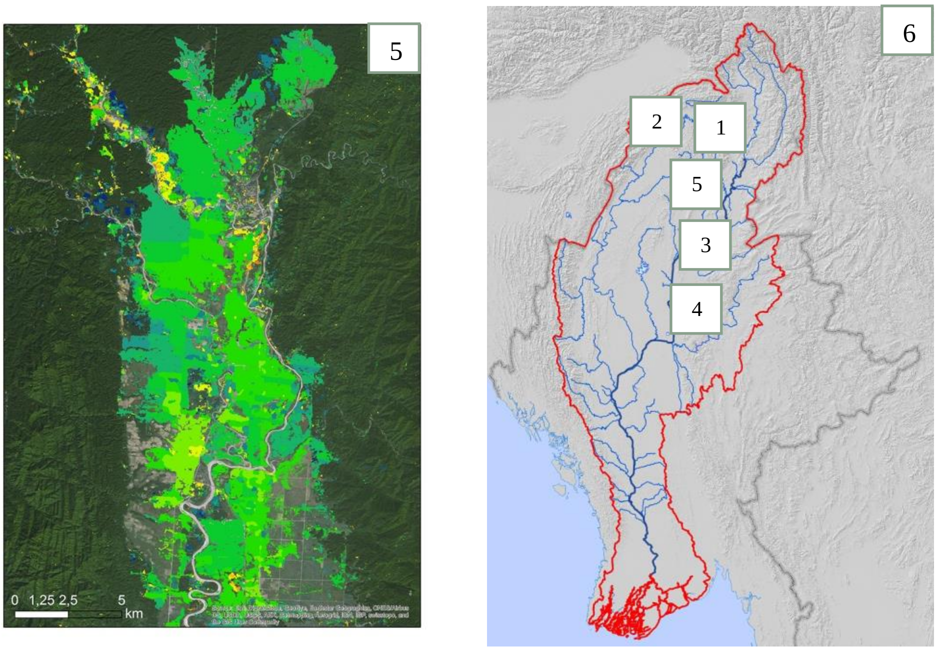


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Figure 3.5 - Oblique Google Earth image showing an area of the Central Dry Zone (downstream of Old Bagan) with dry river channels that appear to contribute large volumes of sediment on an episodic basis

Deforestation in the delta, particularly of the coastal mangrove forests, presents additional geomorphic risk, as the mangroves provide stability to the delta front and are the first line of defence against extreme storms, cyclones, storm surges, or tsunamis. Leimgruber et al., (2005) identified the Ayeyarwady Delta as a deforestation hotspot, finding that 20% of the mangroves were lost from 1990 to 2000, with the demand for fuelwood cited as a principle driver. Webb et al., (2014) documented the progressive decline of mangroves on the Ayeyarwady Delta between 1978 and 2011, and found similarly high rates of deforestation and identified expanding agriculture as a principle driver into the future.

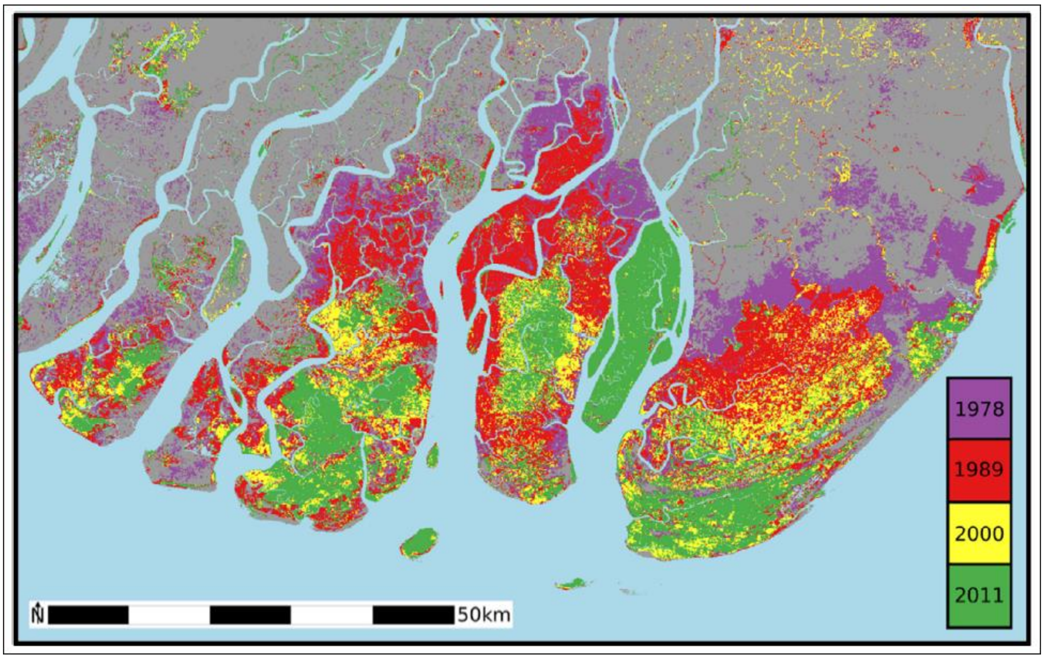


Figure 3.6 - Distribution of mangroves in the Ayeyarwady Delta (Web et al., 2014)

3.2 Terrestrial Mining

Mining activities have the potential to increase sediment inputs to river systems through the large-scale disturbance of land surfaces that can increase erosion and alter flow patterns. Reshaping the land surface is often required to remove large volumes of over-burden to access the underlying mineral resource. These piles of waste rock can provide high sediment inputs to rivers as they erode, as well as alter other water quality parameters. Mines that post process ores and generate mine tailings pose an additional sediment input risk if these materials are not stored in long-term secure repositories. Alluvial mining, where unconsolidated sediments are processed to extract mineral particulates, poses a substantial risk to river systems, as the target material is frequently located in active alluvial deposits along the banks or floodplains of rivers, and the waste is typically deposited within the river channel or along the banks where it is mobilised in subsequent high flow events. If mining areas are not rehabilitated such that the landscape is returned to a stable configuration, mining inputs and impacts can persist for decades after the cessation of mining activities.

Increasing sediment inputs to rivers from mining have the same geomorphic impacts as increasing sediment input from other land use changes; rivers can become choked, and the elevation and slopes of riverbeds can be altered. Mining inputs can be fine- or coarse-grained, and thus have the potential to impact both the suspended and bedload components of river system.

Myanmar is known as an important country for its mineral wealth. Lead, silver, zinc, tin, tungsten, and gems have been mined since the fifteenth century (Moody, 1999). The recorded value of exports of gas, oil, coal, jade, gems, metals, and wood made up about 70% of national exports (Aung Lynn et al., 2014).

In Myanmar in general, and the Ayeyarwady in particular, gold and jade mining have created the greatest impacts in the river due to their ubiquity and the methods of extraction, which target alluvial deposits and can alter riverbeds. Examples of land disturbance associated with these activities are shown in

Figure 3.7.

Figure 3.7 - Small scale alluvial gold mining in the Ayeyarwady near Myitsone (Injangyang township, Kachin state) on the N'mai Hka and (right) larger scale mining in the Ayeyarwady near Shwe Kyin (Singu township, Mandalay division)

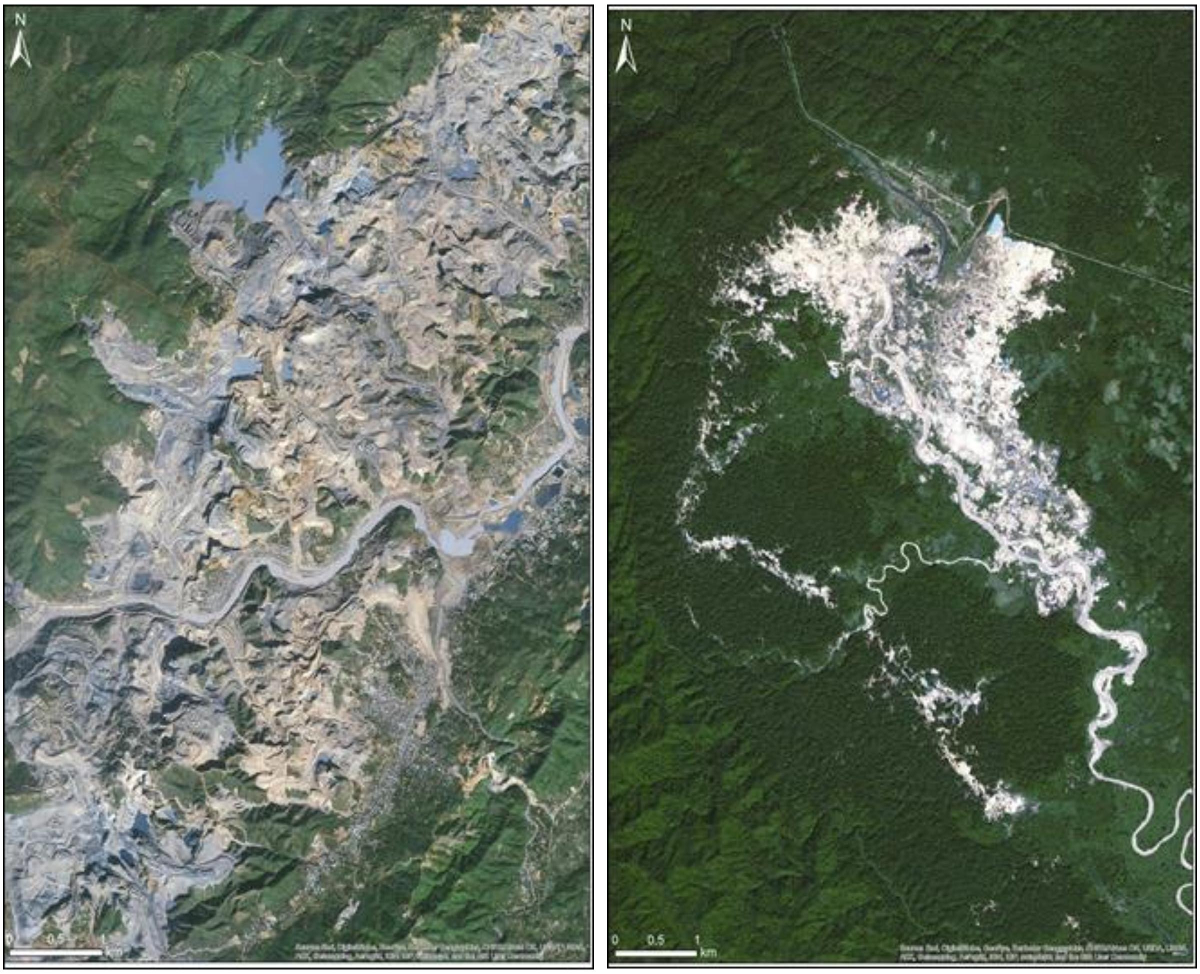


Figure 3.8 - Mining in the tributaries of the Chindwin Jade mining near (left) Hpakant in the Uyu River catchment and (left) gold mining near the Tawa Hka River (source: Google Earth)

Mining has impacts at different scales. Jade mining in the Uyu tributary is implemented at a large scale using earthmoving equipment that causes extensive impacts to the land and river as the mining spoils are disposed in the river. These deposits choke the river and have increased flooding due to the resulting reduction in channel capacity. Similar impacts are associated with gold mining, which occurs on the bed, banks and terraces of the rivers. The dredge spoils create waste piles and the pits and shafts on the banks and terraces cause erosion and siltation through disturbance of fine as well as coarse materials. Impacts include changes to the elevation of the riverbed and range of seasonal water levels, and shifts in the pattern of erosion and deposition within the channel. Sluicing and hydraulic mining also extract water from the rivers for mining and washing, which is frequently returned with high levels of sediment (Images Asia Environment Desk and Pan Kachin Development Society, 2004).

The SOBA 3 investigations focused on providing an overview of the distribution and density of mining areas within sub-catchments with the aim of understanding potential sources of sediment to the river. Mining areas were mapped using Landsat images with a resolution of 30 m. The analysis included dry season images from 1988, 1995, 2000, 2005, 2010, and 2016 when cloud cover was low. The mapping was made manually by visual interpretation because remote sensing techniques do not distinguish between soil denudation by mining, deforestation, cultivation, or deposition from rivers due to the large heterogeneity of soil colours (wave length) and land uses. Mining boundaries were digitised at a scale of 1:25,000 across the catchment to provide uniformity. ASTER L1T imagery, with a resolution of 15 m, was available for 2016 and included in the analysis. Google Earth imagery was used to verify the findings. Polygons were drawn around each mine site based on visual identification of mining features including bare ground with pits and piles of earth, large machinery, and water ponds.

Over 1,200 km^2 of mining areas were identified for the 2015 to 2016 period, including 816 km^2 on the Chindwin and 127 km^2 on the Mu River. The distribution of mines was mapped by sub-catchment and show that the main area for mining occurs on the Chindwin River, which accounts for about 68% of the total area disturbed by mining with the Mu River containing the second largest area of mining disturbed land.

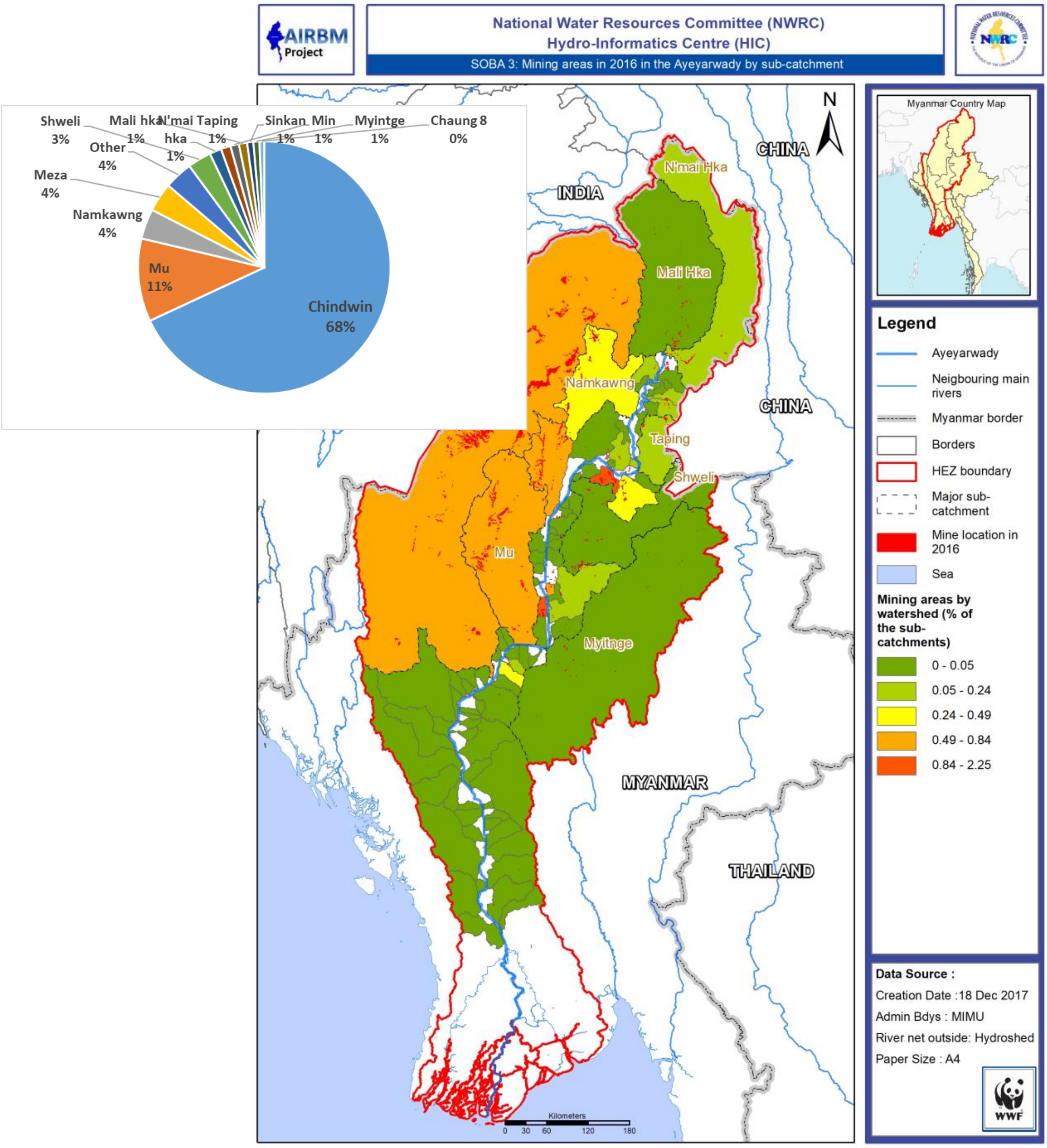


Figure 3.9 - Distribution of mining affected landscapes in the sub-catchments of the Ayeyarwady in 2016. (top) by geographic distribution and (bottom) proportion of total disturbed land ***(Analysis based on Landsat imagery)***

The area of disturbed land in each of the satellite images between 1988 and 2016 has been quantified to provide a time series of mining development in the Ayeyarwady. The results show an exponential increase in land areas affected by mining with about 1,200 km^2 in the Ayeyarwady catchment, with over 800 km^2 of the development occurring within the Chindwin.

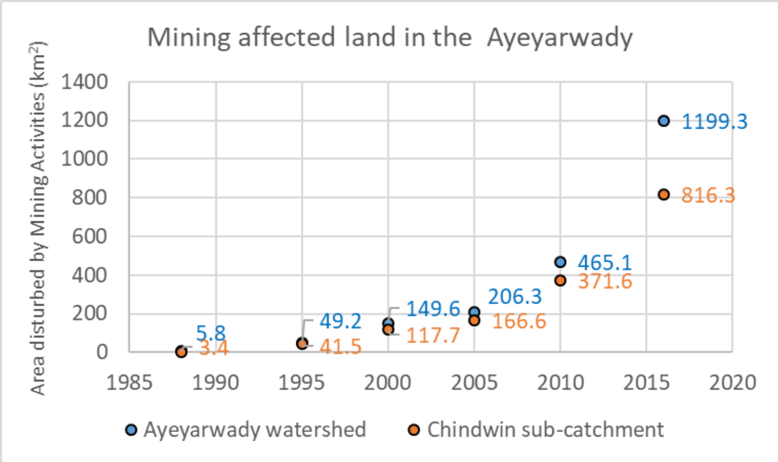


Figure 3.10 - Time series of mining affected land in the Ayeyarwady and Chindwin based on satellite imagery

Figure 3.11 - Oblique Google Earth image showing inflow of high sediment bearing tributaries in the Sagaing fault zone, and area disturbed by mining along the riverbank (top right area of photo) Tributary catchments are altered due to extensive mining and other land use changes resulting in a high influx of sediments

Overall land use changes have likely increased the availability of sediment in the Ayeyarwady and altered its characteristics. Land use induced changes occur on a local scale, but can have large-scale impacts on river systems as changing the volume and characteristics of the sediment load alters the flow requirements needed to move the material through the system.

3.3 Hydropower and Irrigation Developments

Activities that establish weirs or dams in rivers have the potential to change the flow regime and reduce the sediment load of the river, thus altering the sediment transport and the geomorphology of the river system.

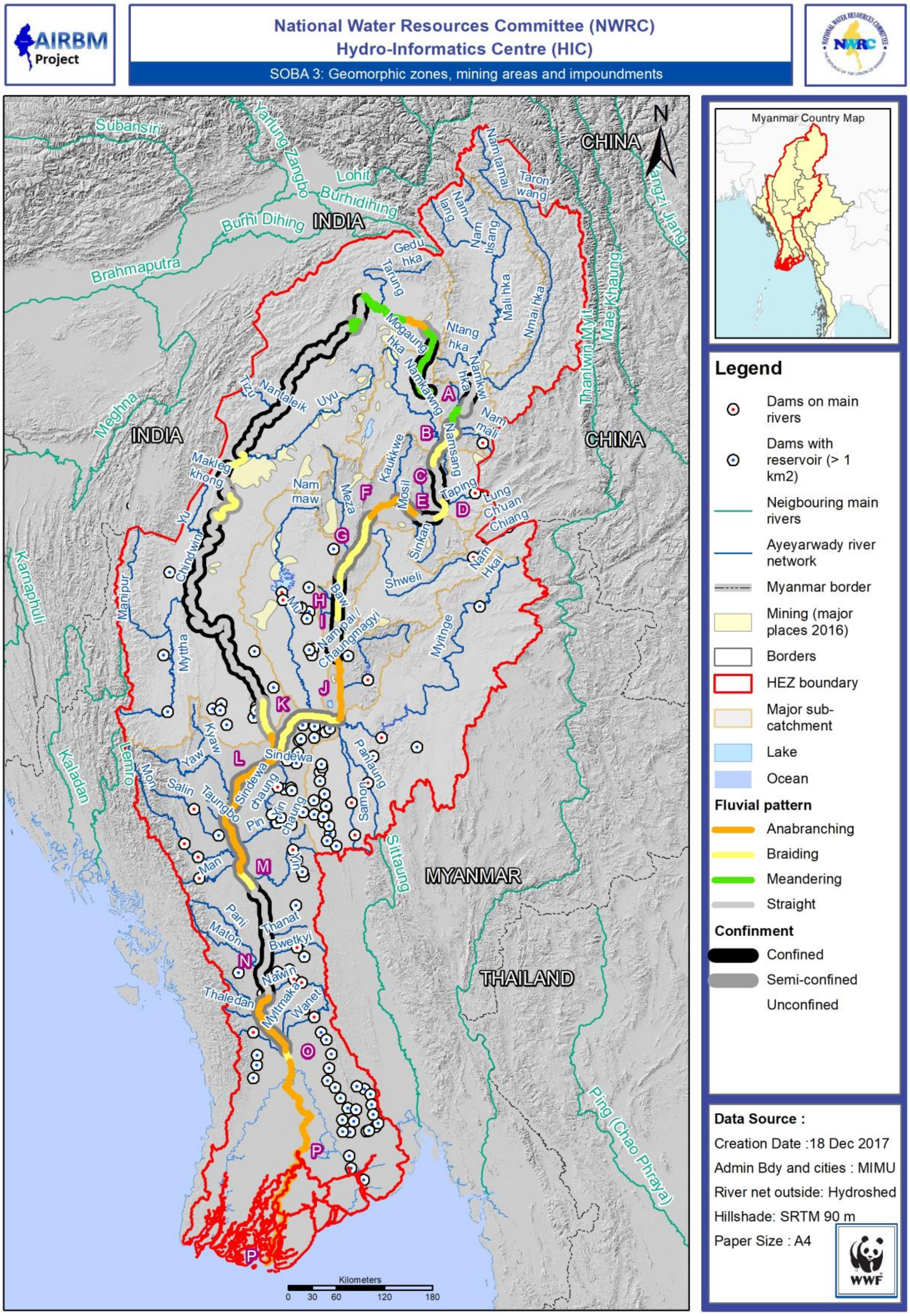


Figure 3.12 shows impoundments with surface areas >1km² based on an analysis of satellite imagery, and includes water bodies associated with both hydropower and irrigation. In general, hydropower dams and

impoundments are in the northern and western mountainous areas of the catchment, while irrigation impoundments are more common in the drier, lower Ayeyarwady.

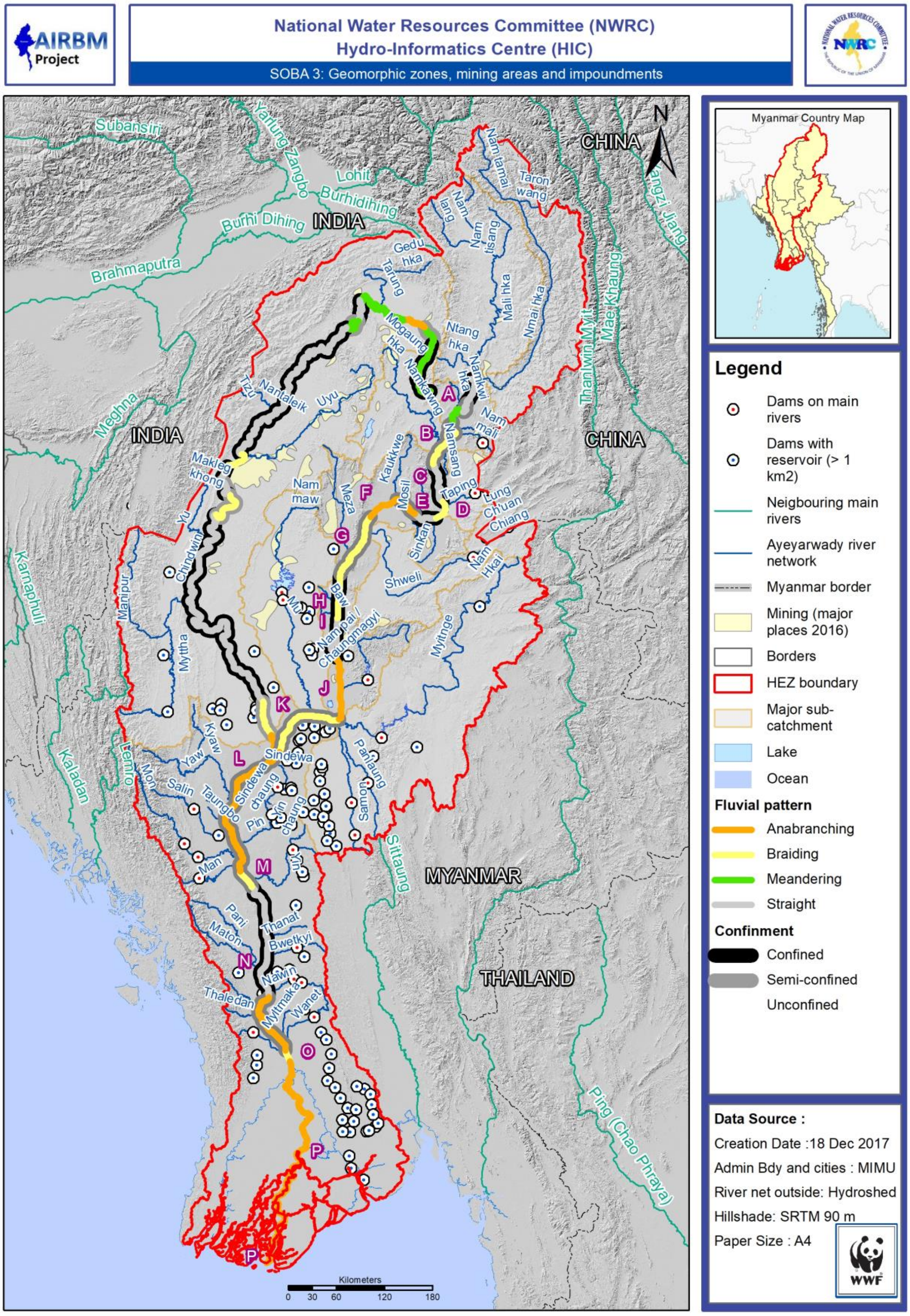
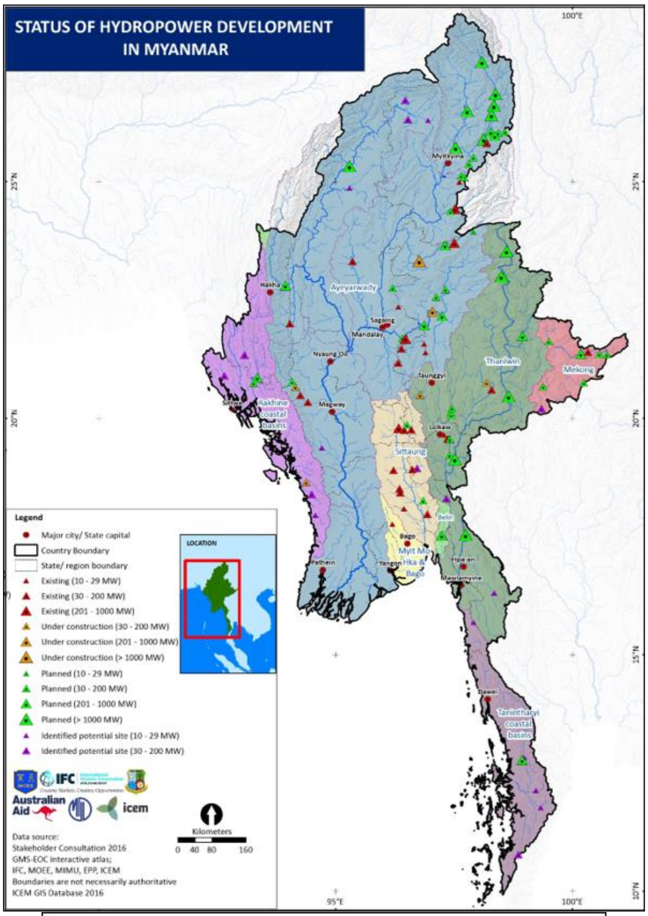


Figure 3.12 - Catchment maps showing locations of dams and impoundments with >1 km^2 surface area on the Ayeyarwady and tributaries, including areas outside of Myanmar

Dams include both hydropower and irrigations. Geomorphic zones shown for reference. (Analysis based on satellite imagery)


STATUS OF HYDROPOWER DEVELOPMENT IN MYANMAR
Ayeyarwady
Sittaung
Thanlwin
Mekong
Rakhine coastal basins
Tanintharyi coastal basins
Bilin
Myit Ma Hka & Bago
Legend
Major city/ State capital
Country Boundary
State/ region boundary
Existing (10 - 29 MW)
Existing (30 - 200 MW)
Existing (201 - 1000 MW)
Under construction (30 - 200 MW)
Under construction (201 - 1000 MW)
Under construction (> 1000 MW)
Planned (10 - 29 MW)
Planned (30 - 200 MW)
Planned (201 - 1000 MW)
Planned (> 1000 MW)
Identified potential site (10 - 29 MW)
Identified potential site (30 - 200 MW)
LOCATION
Kilometers
0 40 80 160
Data source:
Stakeholder Consultation 2016
GMS-EOC interactive atlas;
IFC, MOEE, MIMU, EPP, ICEM
Boundaries are not necessarily authoritative
ICEM GIS Database 2016

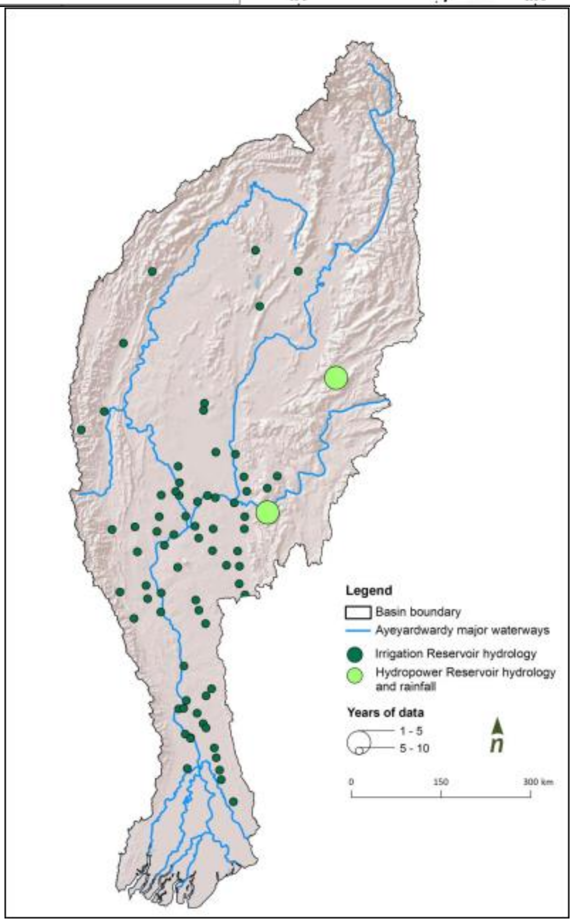
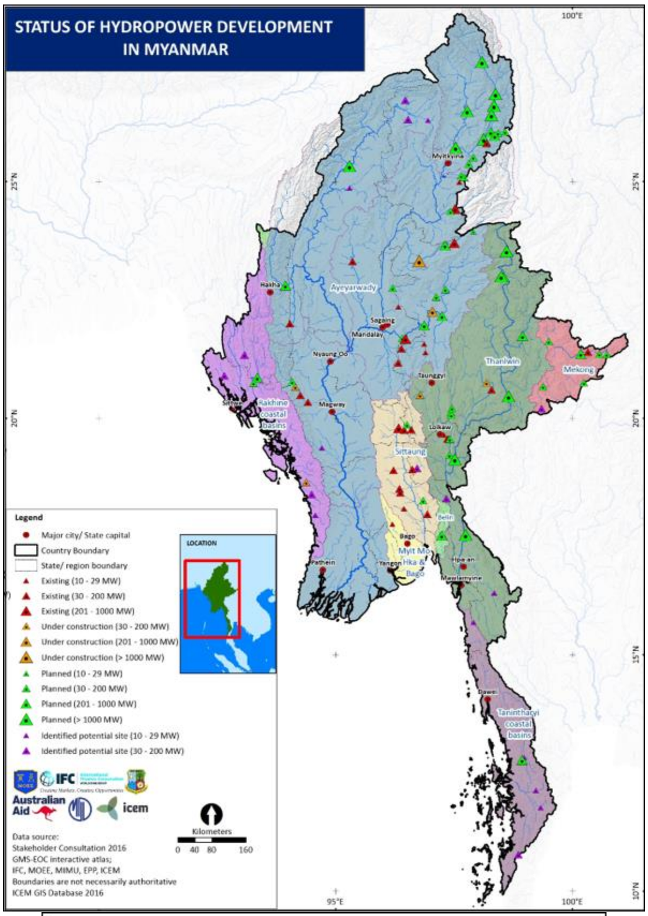

Legend
Basin boundary
Ayeyardwardy major waterways
Irrigation Reservoir hydrology
Hydropower Reservoir hydrology and rainfall
Years of data
1 - 5
5 - 10
0 150 300 km

Figure 3.13 - (left) Existing and 'planned' hydropower developments in Myanmar. Symbol size and colour indicates whether projects are existing or planned and the size of the power development. Ayeyarwady basin is shown in blue (IFC et al., 2017); (Right) Irrigation impoundments in Myanmar (Alluvium and Hydronumerics, 2017)

3.3.1 Hydropower

Hydropower directly affects the geomorphic functioning of rivers by altering flow patterns and reducing sediment loads due to trapping in impoundments. The larger grain-size fractions of sand and gravels are more effectively trapped in impoundments because they are typically transported as bedload, thus hydropower development also has the potential to alter the characteristics as well as the volume of sediment transported downstream.

There are 2,018 megawatts (MW) of installed hydropower capacity in the Ayeyarwady River catchment, with an additional 1,372 MW of capacity under construction (ICEM, 2017). The existing development is focused in the Ayeyarwady upstream of the confluence with the Chindwin, with the exception of the cascade development in the Mone Chaung sub-basin, located in the lower Ayeyarwady (Table 3,


STATUS OF HYDROPOWER DEVELOPMENT
IN MYANMAR
Legend
Major city/ State capital
Country Boundary
State/ region boundary
Existing (10 - 29 MW)
Existing (30 - 200 MW)
Existing (201 - 1000 MW)
Under construction (30 - 200 MW)
Under construction (201 - 1000 MW)
Under construction (> 1000 MW)
Planned (10 - 29 MW)
Planned (30 - 200 MW)
Planned (201 - 1000 MW)
Planned (> 1000 MW)
Identified potential site (10 - 29 MW)
Identified potential site (30 - 200 MW)
LOCATION
Kilometers
0 40 80 160
Data source:
Stakeholder Consultation 2016
GMS-EOC interactive atlas;
IFC, MOEE, MIMU, EPP, ICEM
Boundaries are not necessarily authoritative
ICEM GIS Database 2016
Ayeyarwady
Thanlwin
Mekong
Sittaung
Myitkyina
Sagaing
Mandalay
Taunggyi
Magway
Bago
Yangon
Pathein
Dawei
Loikaw
Hpa-an
Mawlamyine
100°E
95°E
25°N
20°N
15°N
10°N

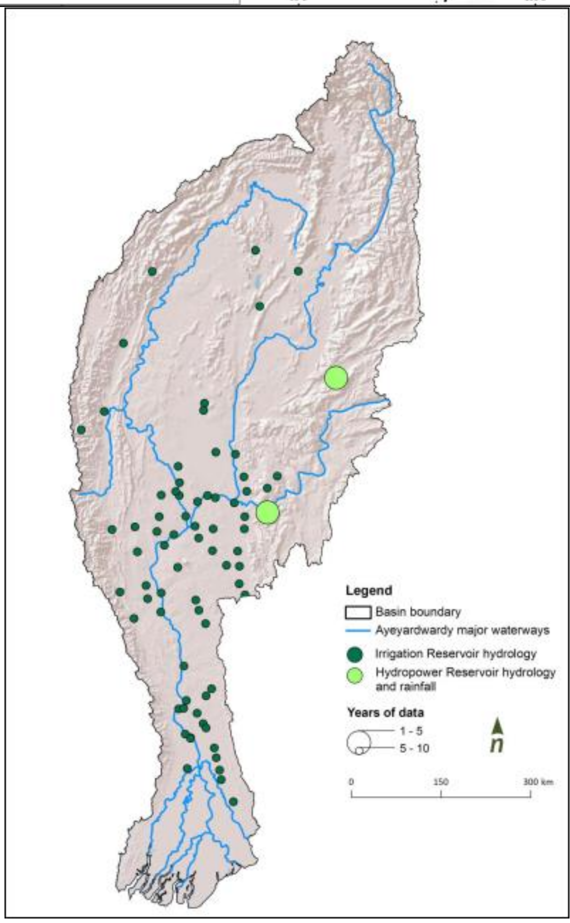

Legend
Basin boundary
Ayeyardwardy major waterways
Irrigation Reservoir hydrology
Hydropower Reservoir hydrology and rainfall
Years of data
1 - 5
5 - 10
n
0 150 300 km

Figure 3.13). The largest existing project is Yeywa, which was commissioned in 2010. The majority of the generated power is consumed in Myanmar, with about 500 MW exported to China. The planned expansion of hydropower as shown on the map is discussed in the Trend Assessment Section (Section 5.3.3).

Table 3 - Summary of existing and under construction hydropower projects in the Ayeyarwady Basin

Hydropower Project Name	Installed Capacity (MW)	Sub-basin	Status
Chipwi Nge	99	Ayeyarwady Headwaters	Built
Mali	11	Mali Creek	Built
Dapein 1	240	Dapein	Built
Shweli 1	600	Shweli	Built
Shweli 3	1,050	Shweli	Under construction
Sedawgyi	25	Built	Built
Yeywa	790	Myitnge	Built
Yeywa (upper)	280	Myitnge	Under construction
Zawgyi I	18	Myitnge	Built
Zawgyi II	12	Myitnge	Built
Kinda	56	Myitnge	Built
Myogyi	30	Myitnge	Built
Thapanzeik	30	Mu	Built
Buywa	42	Mone Chaung	Under construction
Kyee Ohn Kyee Wa	74	Mone Chaung	Built
Mone Chaung	75	Mone Chaung	Built

An example of typical flow changes associated with hydropower development is provided by comparing the inflow and outflow from the Yeywa hydropower project (

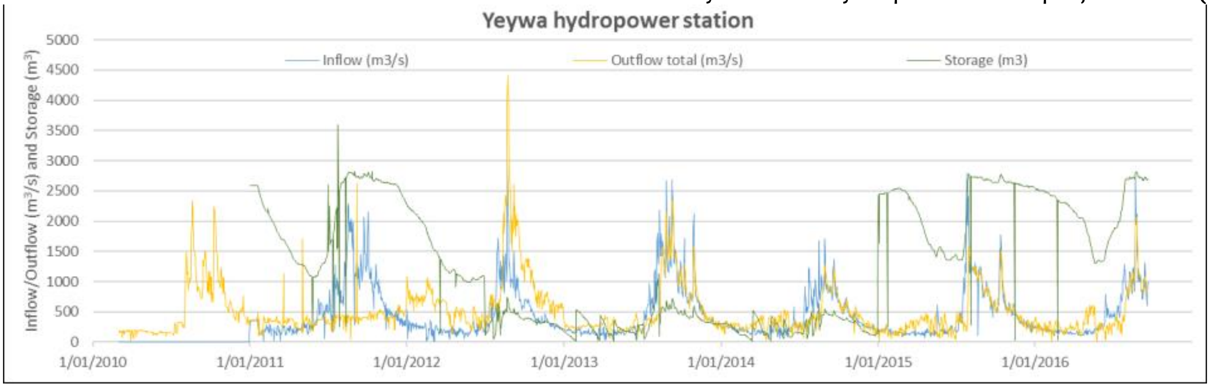


Figure 3.14). Changes to the hydrograph include a delay to the timing of the onset of high flows, changes to the magnitude of outflows (both higher and lower) relative to inflows, and increases to the average dry season discharge. These types of flow alterations can affect the volume and timing of sediment movement. The high-volume spill events are especially important for geomorphic change. While these may pass natural flood events through impoundments, they can lead to high levels of erosion in the downstream river, due to the high erosive capacity of the flows combined with a lack of sediment available for deposition during the receding limb of the event.

The full geomorphic impacts from hydropower projects can take years to decades to occur, largely due to the large volume of sediment stored in the downstream river channels that can buffer impacts for extended periods. Geomorphic impacts associated with the existing level of development have not been quantified in the Ayeyarwady, however some level reduction to bedload and suspended sand transport has likely occurred in the catchments where hydropower has been developed, and there is some evidence pointing to changes consistent with hydropower development. For example, changes in the planform of the Shweli River, where hydropower was established in Myanmar in 2008 and in China prior to then, show major changes between 1984 and 2016 that are consistent with either 1) a large reduction in sediment supply, 2) a change to the flow regime, or 3) a reduction in the base level of the Ayeyarwady River (

Figure 3.15).

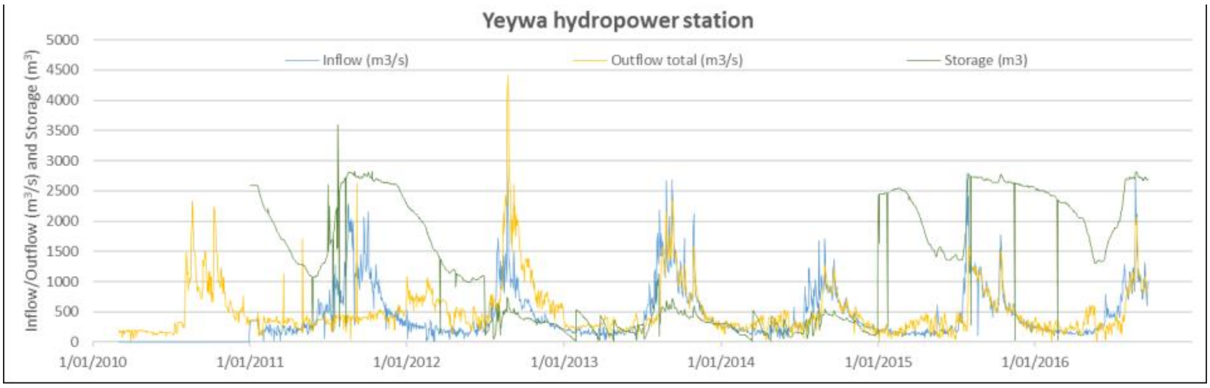


Figure 3.14 - Inflow /outflow and storage in the Yeywa hydropower scheme in the Myitnge Plots show differences between inflow and outflow volumes (Alluvium and Hydronumerics, 2017)

Figure 3.15 - Google Earth images of the confluence of the Shweli and Ayeyarwady Rivers in 1984 (top) and 2016 (2016) Comparing the images shows a straightening of the Shweli river channel, which is consistent with a decrease in upstream sediment supply.

3.3.2 Irrigation

Irrigation impoundments can alter river flows and trap sediments similarly to hydropower, and many of the schemes in Myanmar are multi-use, supplying irrigation supply as well as hydropower generation, such as the Thapanzeik scheme in the Mu River and the lowest project in the Mone Chaung cascade. Alluvium and Hydronumerics (2017) identified approximately 70 irrigation schemes with hydrologic information, but many additional schemes are likely to exist. Developing a full list of schemes would be useful, including storage volumes and release patterns to better understand the potential impact of irrigation on the river. This is considered a data gap, and is discussed further in Section 7.

Figure 3.16 - Photos of irrigation off takes and infrastructure in the Ayeyarwady

3.4 Sand Mining

Sand is the most exploited commodity after water in the world (Global Environmental Alert Service, 2014). It is required for most construction activities, used for the establishment of road bases, and remains a major component of asphalt and the material of choice for land filling, reclamation and replenishment of eroding beaches around the world. River sand is chosen for most of these activities due to its range of grain-sizes, irregular shape (as compared to desert sand), and lack of sodium content (as compared to marine sand). The rapid development in Myanmar is fuelled by the availability of sand, and its major rivers are being targeted to provide this valuable resource.

Just as sand provides stability to infrastructure projects, buildings and land fill, it also provides stability to riverbanks and channels. The removal of sand and gravel can decrease channel depth, leading to instability of the nearby riverbanks. Changes to channel depth and slope are also prone to propagate upstream and downstream, affecting channel and bank stability far from the sites of extraction. The Ayeyarwady is particularly susceptible to channel changes associated with sand and gravel extraction or dredging due to the grade of the lower river, which is generally controlled by friction rather than hard hydraulic controls (e.g. bedrock channels or man-made structures). Any increase in the channel cross-section associated with sand mining or dredging will decrease friction, increase water velocities, increase sediment transport, and lower upstream water levels.

These processes have the potential to alter the magnitude and pattern of sediment delivered to the delta. In the Mekong River, investigations have linked large-scale changes to the delta to sediment extraction, combined with the impact of upstream hydropower impoundments, and ground water extraction. Bravard et al., (2014) documented the extraction of approximately 50 Mt of sand and gravel per year from the river, based on surveys of operators at extraction sites. The results are conservative due to under reporting. The extraction of these large volumes of material have directly and indirectly altered the depth and morphology of channels in the delta, with channel deepening and a net loss of ~200,000 m^3 of material between 1998 and 2008 in the two main channels within the delta (Brunier et al., 2014). Aggregate mining combined with other catchment changes is also linked to changes to the delta front, where erosion rates of 12 metres per year have been recorded in areas where accretion of up to 20 metres per year was previously recorded. In areas where accretion is occurring, it is attributed to the reworking of coastal deposits under a regime of decreasing sediment supply (To gain an understanding of the distribution of sand extraction activities in the Ayeyarwady and estimates of the grain-sizes and volumes being extracted, the SOBA 3 Team implemented two investigations. The first was based on the analysis of satellite imagery to identify areas in the river where sand mining has been active over the past two years. Based on these results, and recognising that larger cities are likely to have larger demands for sand and gravel and act as major distribution centres, a survey of sand and gravel distributors was developed and implemented. The survey was targeted at sand and gravel suppliers because the timing of the SOBA project coincided with the wet season, when sand and gravel extraction from the river is at a minimum due to high water levels and flow velocities. A copy of the survey form used by the SOBA 3 Team along with a report summarising the field activities is included in Annex 4.

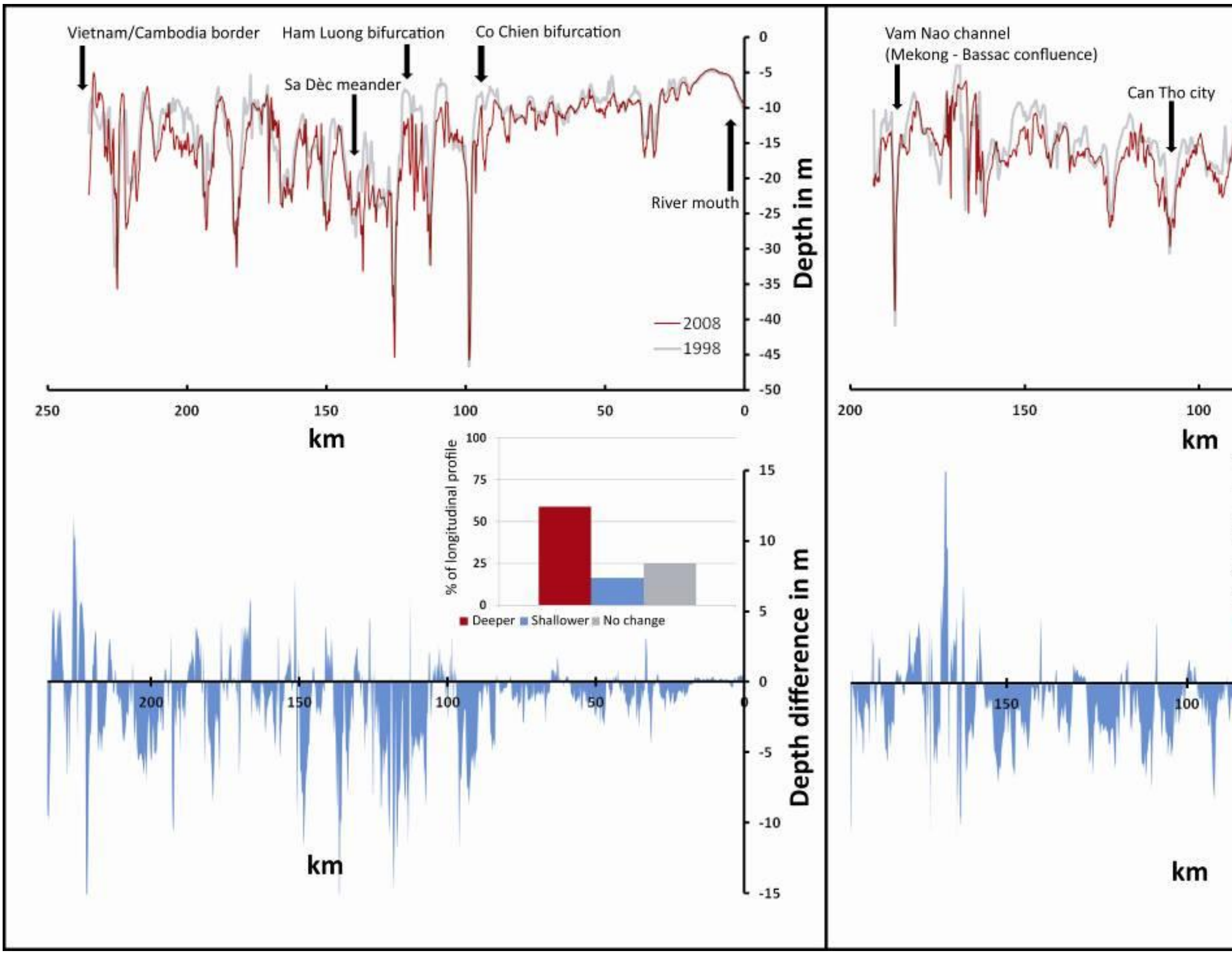


Figure 3.17; Anthony et al., 2015).

To gain an understanding of the distribution of sand extraction activities in the Ayeyarwady and estimates of the grain-sizes and volumes being extracted, the SOBA 3 Team implemented two investigations. The first was based on the analysis of satellite imagery to identify areas in the river where sand mining has been active over the past two years. Based on these results, and recognising that larger cities are likely to have larger demands for sand and gravel and act as major distribution centres, a survey of sand and gravel distributors was developed and implemented. The survey was targeted at sand and gravel suppliers because the timing of the SOBA project coincided with the wet season, when sand and gravel extraction from the river is at a minimum due to high water levels and flow velocities. A copy of the survey form used by the SOBA 3 Team along with a report summarising the field activities is included in Annex 4.

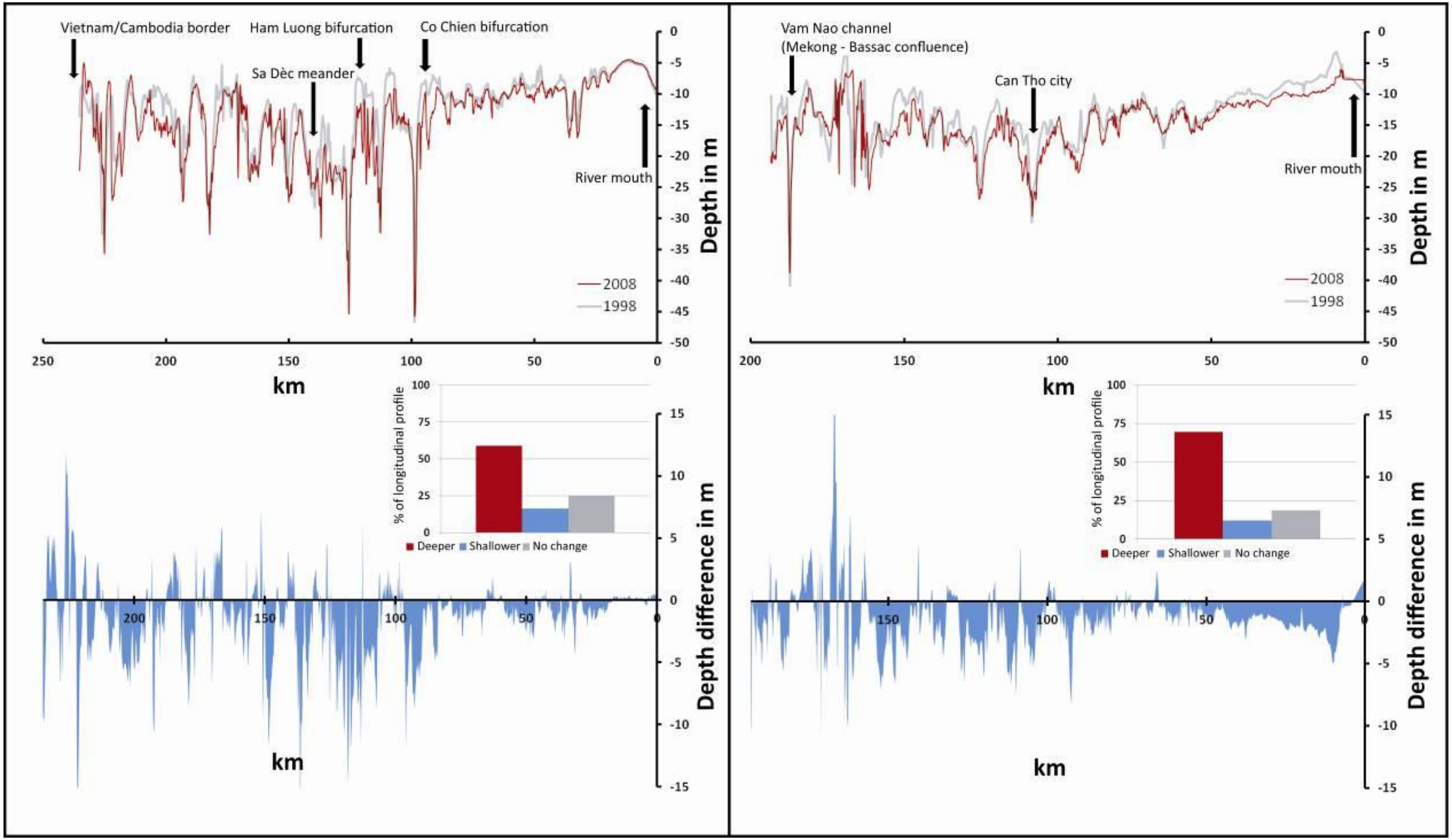


Figure 3.17 - Morphology (top panels) and depth changes (bottom panels) of the thalwegs of the Mekong (A) and Bassac (B) channels in 1998 and 2008. *(Source: Brunier et al., 2014)*

3.4.1 *Identification of sand mining locations using satellite imagery*

During the SOBA 3 field excursion, the team observed numerous sites of sand extraction, with the

occurrence increasing downstream of Mandalay (e.g.

Figure 3.18). To identify areas recently exploited for sand and gravel, and to gain a preliminary understanding of the density and permanency of the activity, high-resolution satellite imagery was interrogated. The image analysis was based on the field observation that sand dredges and associated barges occur in consistent and recognizable patterns, with dredges clustered in close proximity to one another and barges typically moored a short distance away. A full description of the types of satellite images used and the method developed for the analysis is contained in Annex 3.

Figure 3.18 - Sediment extraction upstream of Pyay

High resolution (10 m) imagery from the Sentinel 2 satellite was used for the image analysis with the area investigated bounded by the Inwa bridge, near Mandalay, and the Bo Myat Tun Bridge, near Nyaungdon, close to the head of the delta. A total of seven cloud free days from November to March over the past two years were identified as suitable for analysis. On each date, the areas occupied by dredgers and barges were identified and surrounded by a polygon. Examples of the areas identified as undergoing repeat sand and gravel extraction are shown in the composite satellite photos in

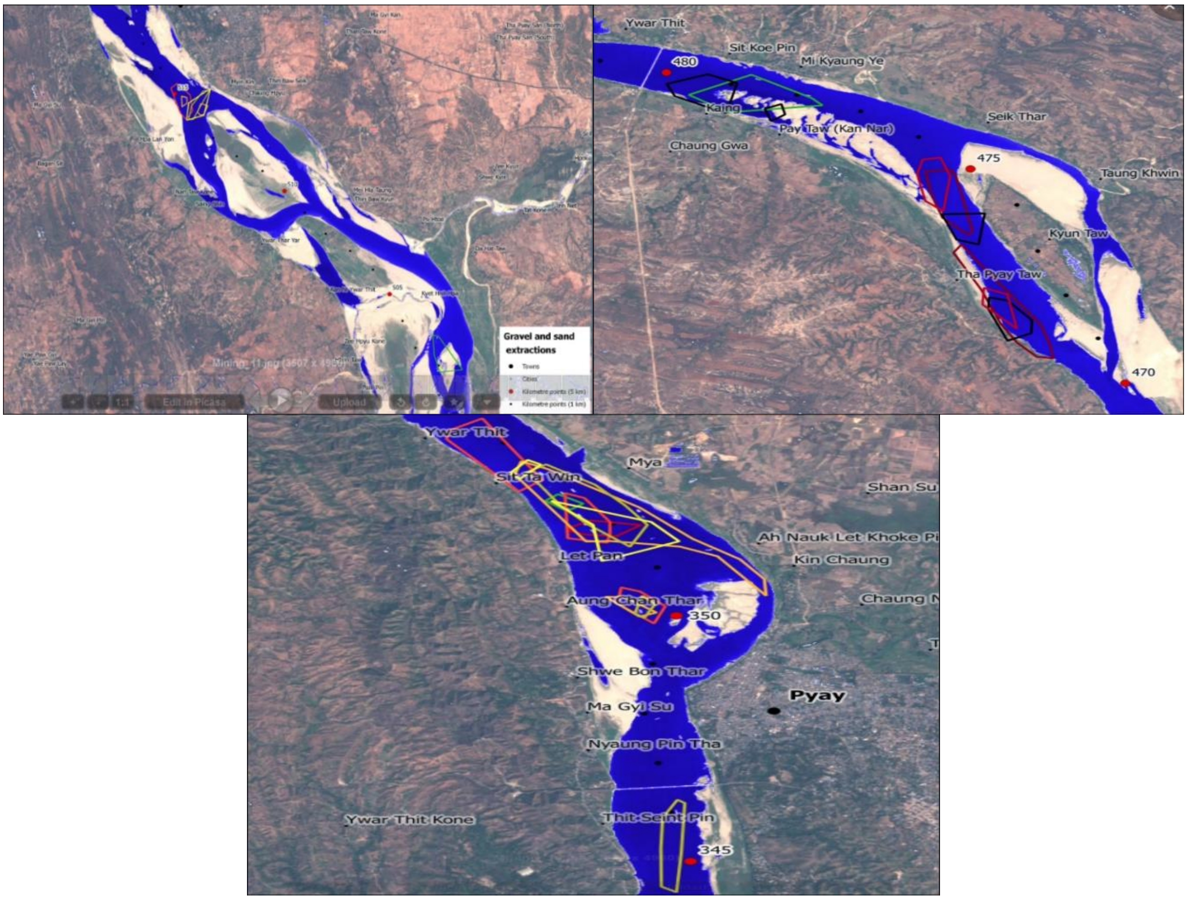
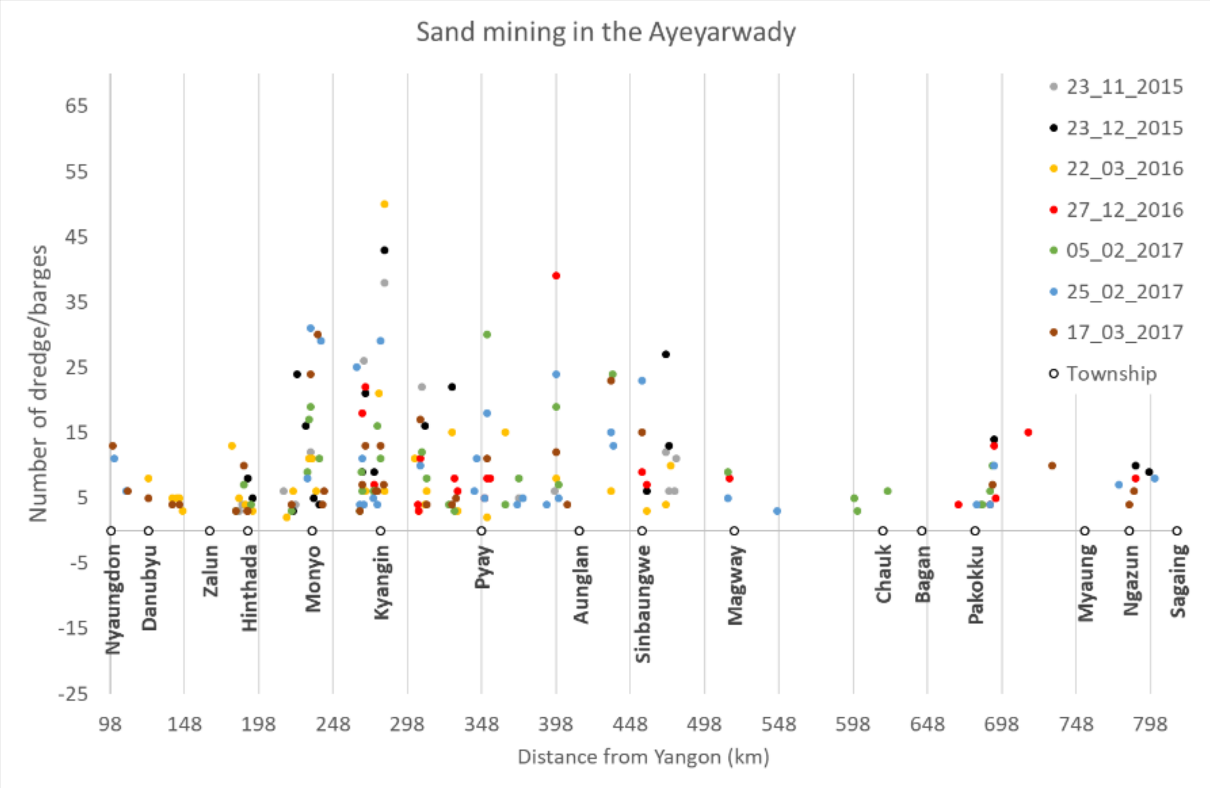


Figure 3.19, while a summary of the image analysis results by date, and combined by 25 km river segments for all dates is shown in



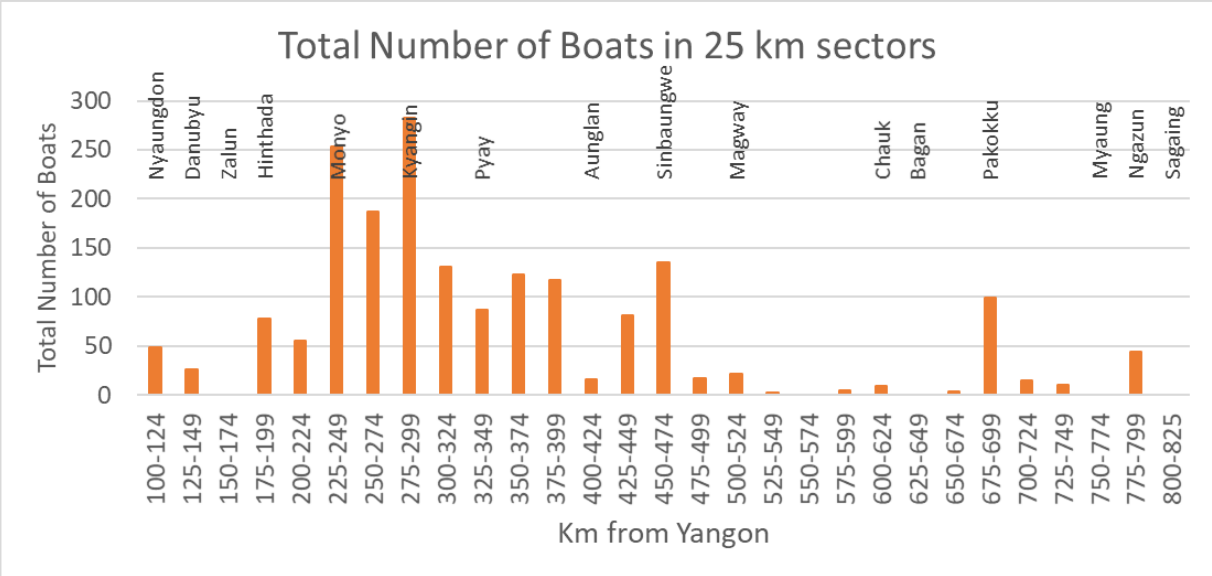


Figure 3.20. A total of 1,849 occurrences of boats associated with sand mining were detected over the seven dates. The survey also found an increasing trend in the number of boats detected over the period, from 182 in November 2015 to 343 in February 2017; however, due to the low number of images and different months being sampled each year, this trend may or may not be accurate.

The analysis identified the area between Hinthada and Magway as the most commonly exploited for sand and gravel extraction, with the highest number of boats during any one date and for the overall period of analysis occurring near Kyangin.

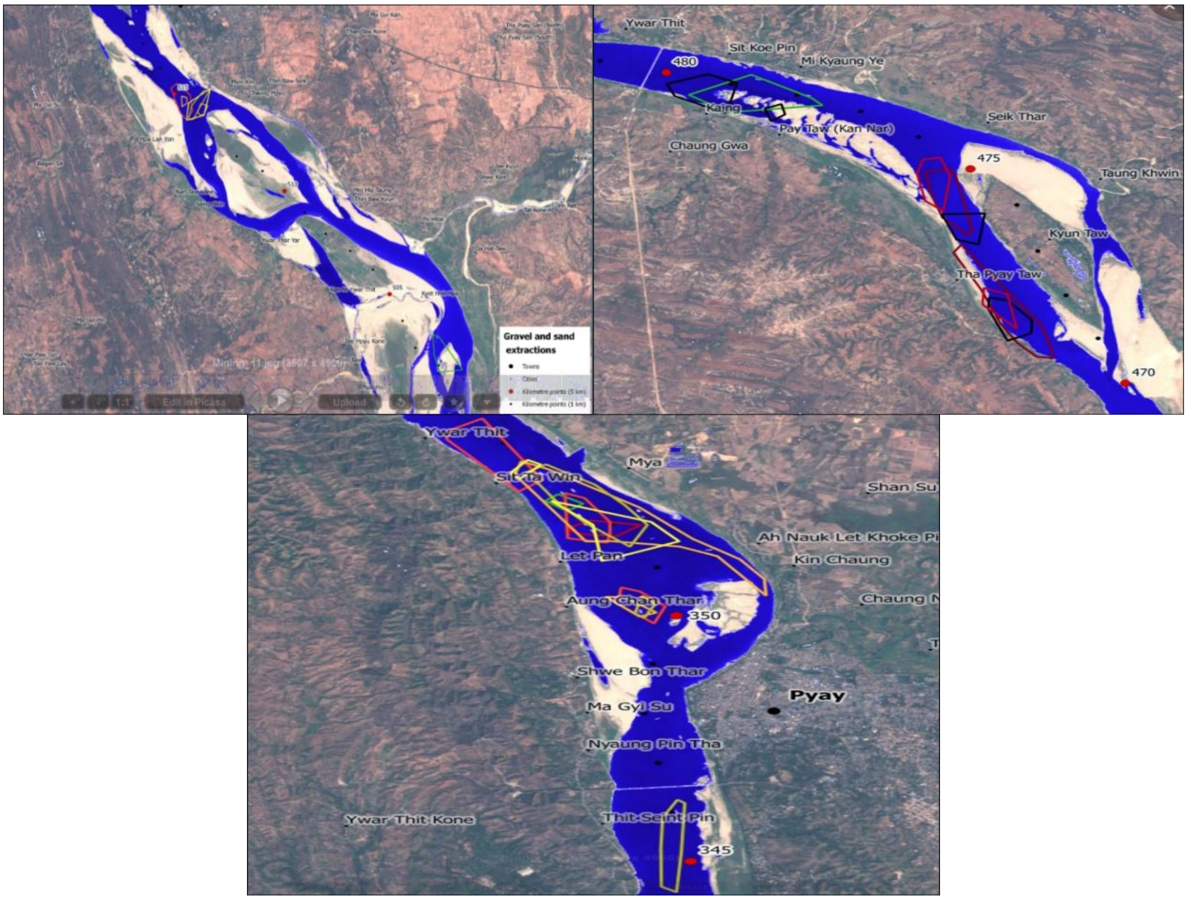
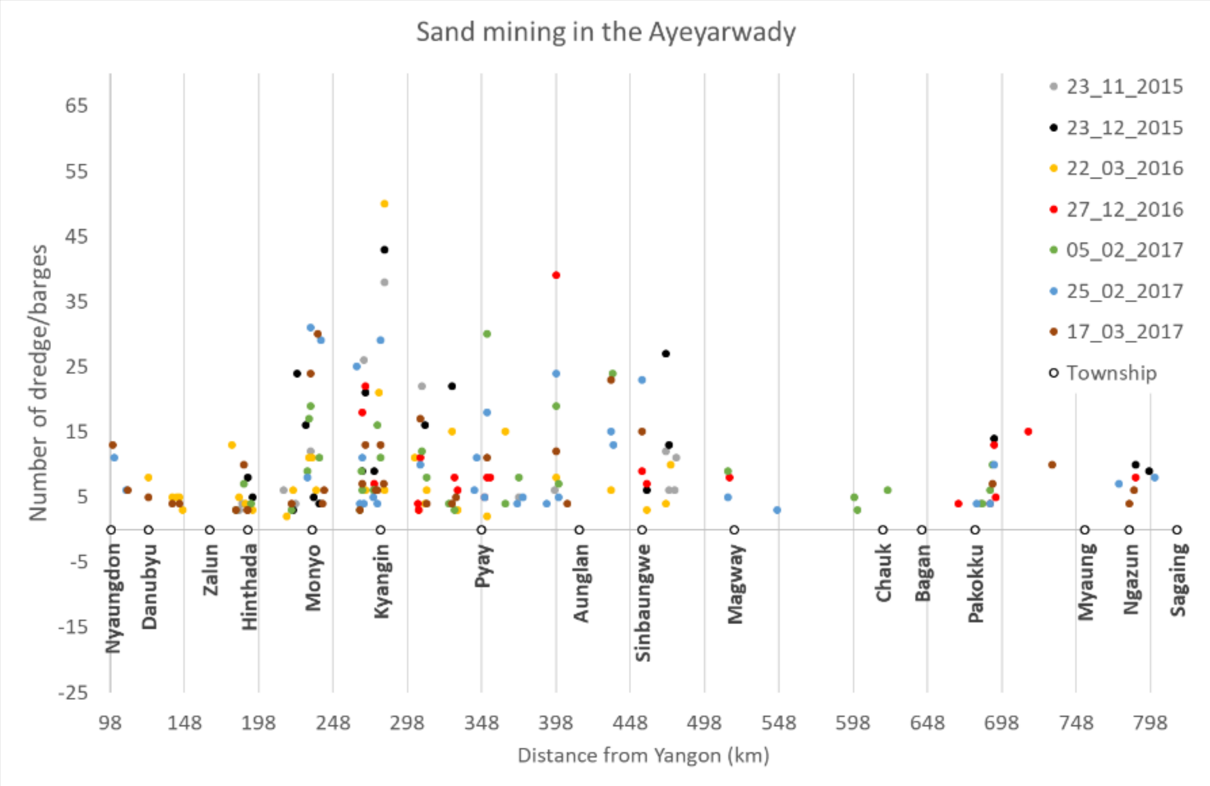


Figure 3.19 - Satellite images showing the polygons where dredges were identified on different dates



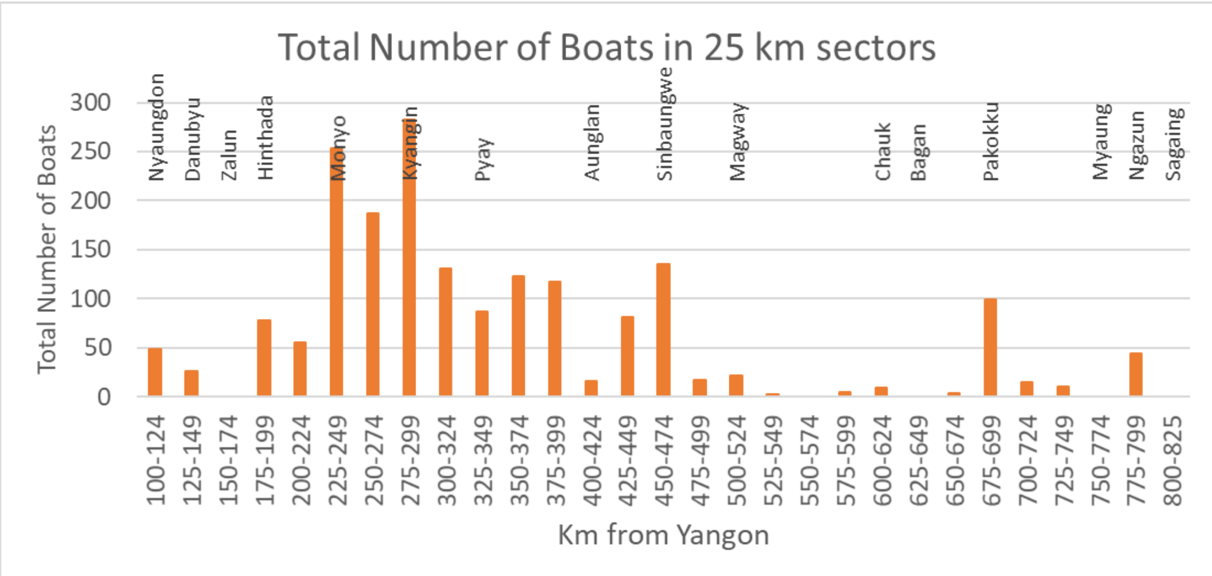


Figure 3.20 - Summary of the number of dredges and barges detected on different dates in satellite images and total number of boats in 25 km sectors

3.5 Results of Sand and Gravel Mining Survey

The sand and gravel mining survey team visited 183 businesses that sell sand and/or gravel between 26 July and 19 August 2017. Distribution centres were targeted, as fewer dredgers operate on the river in the wet season due to higher water levels. The survey included businesses in the regions or districts of Ayeyarwady, Bago, Danubyu, Hinthada, Mandalay, Sagaing, Yangon and Zalon.

Several types of materials are sold at the distribution centres: fine sand, coarser grained construction sand, fine (15 to 20 mm) and coarse (~20 to 200 mm) gravel and pebbles. Photos of gravels and pebbles from Pyay

and the Myitnge River are shown in

Figure 3.21. Fine sand is generally used for non-structural purposes, such as artisanal rendering, and is derived locally around Yangon from the Hlaing River. The other categories are exclusively derived from the Ayeyarwady and Mytinge and are the focus of the survey.

Figure 3.21 - Grain-sizes of (top left) fine and coarse gravels from Pyay, (top right) and fine and coarse gravel from the Myitnge River(bottom) pebbles extracted from the Myitnge River *Length of ruler is 30 cm*

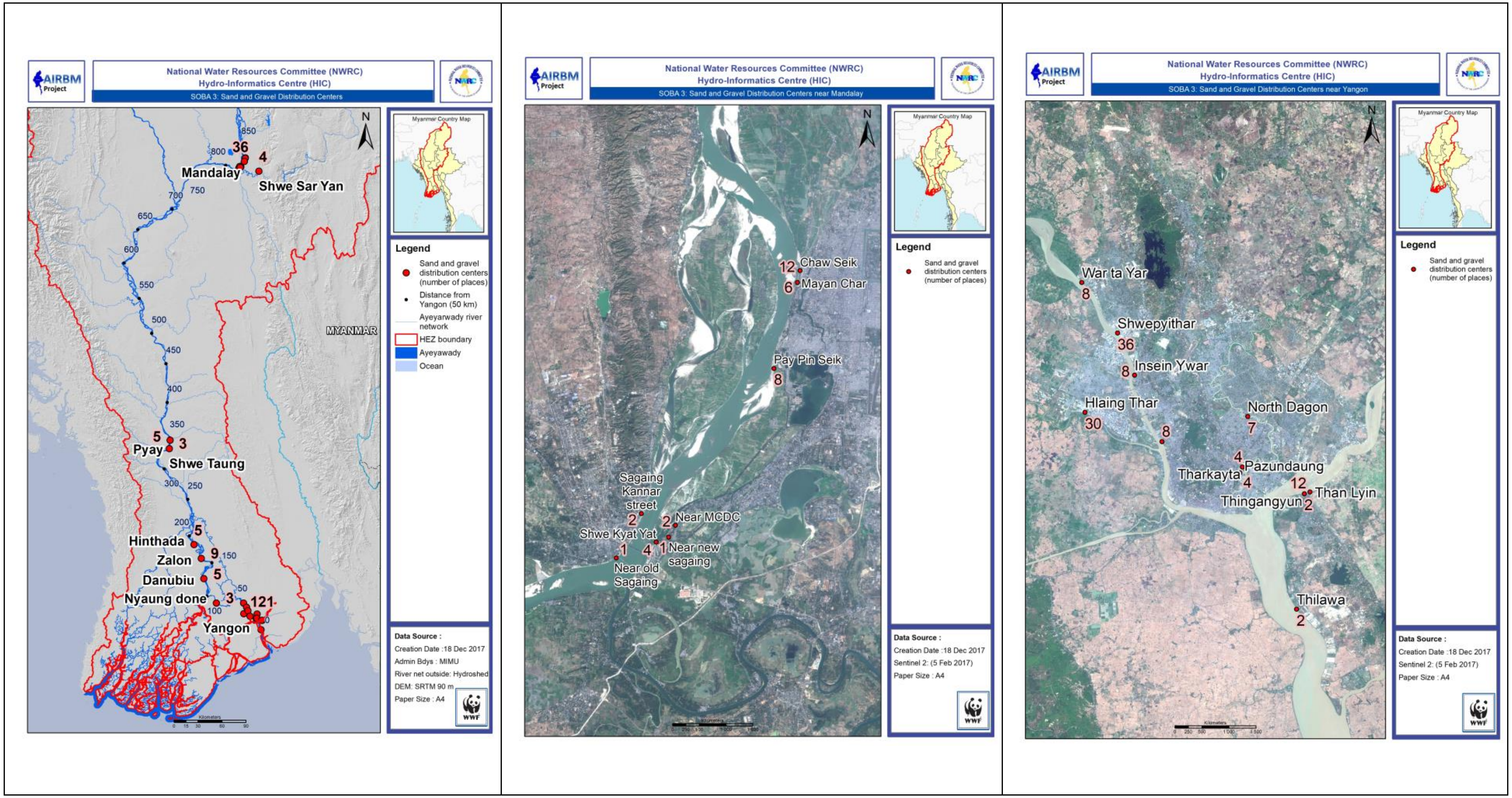


Figure 3.22 - Sand and gravel distribution centres included in the surveyNumbers indicate the number of surveys conducted at each location. ***The satellite images show details around Mandalay/Sagaing and Yangon***

A major issue facing the sand and gravel extraction industry in 2017 during the survey period was the banning of extraction activities in the Ayeyarwady from July to August 2017 by the Government. Based on information obtained from the distributors, the reason for the closure was due to the residents of the local villages complaining that over extraction was leading to bank erosion and high flooding during the rainy season. The survey team was told that the State/Division General Administration Departments, MONREC, and the Directorate of Water Resources and Improvement of River Systems (DWIR) were completing site investigations in the Ayeyarwady. The sudden closure of the river to extraction severely limited supplies to distributors and resulted in a shortage of materials. At the time of the survey, many distributors had exhausted their available inventory of material, and had been forced to shut down, or were limiting sales to small volumes to the immediate area only.

Additional general constraints on sand mining were found to apply to Zalon, where the Government does not allow sand and gravel extraction from the river channel near the town, and distributors acquire gravel supply from operations located upstream on the Ayeyarwady River. Sand mining around Zalon is limited to extraction from exposed sandbanks.

Other descriptive findings of the survey include the following characteristics:

- The industry is regulated through licensing, with the involvement of DWIR, MONREC and the State/Division General Administration Departments. Licenses are linked to specific tracts within the river, defined by coordinates, and include limits on the volume of material that can be extracted from the site.
- Some distributors in the lower Ayeyarwady also sell crushed rock as 'mountain gravel'. The distributors providing this material noted that transport was difficult and there was little price difference between the mountain and river gravels. Mountain gravel was not included in the survey.
- Near Mandalay, no gravel is extracted from the Ayeyarwady, with the source of gravels limited to the banks of the Myitnge River near the km 6 and km 7 beaches. It should be noted that the Yeywa Hydropower Development is located upstream of these sites and will prevent the passage of gravel and pebbles downstream, so eventually this source of gravel will become exhausted.
- Several distributors did not sell sand or gravel to the public, with all extracted material being directed towards large government infrastructure projects. Projects that were specifically identified included four dams near Pyay, the South Nawin Dam project, two additional unnamed dam projects and the new Yangon - Pyay - Magway road. The SOBA 3 Team found this was also true for one gravel mining operation in Myitkyina that was owned and operated by a construction company, as all extracted material was used internally by the private company.

Figure 3.23 - Gravels extracted from the beaches of the Myitnge River near Mandalay

Figure 3.24 - Sand mining near Mandalay

Figure 3.25 - (top) Sand and gravel distributors near Yangon (bottom) barge loaded with gravel and sand extraction from exposed banks along the Ayeyarwady

3.5.1 Survey results

A summary of the survey results is presented in Table 4, with the results presented by townships and summarised by districts or regions. Unsurprisingly, the survey found that the vast majority of the sand was distributed in Yangon, followed by Mandalay and Bago, with gravel also being overwhelmingly distributed in Yangon. The length of operations of the distributors included in the survey ranged from 1 to 37 years, with the averages for each township shown in Table 4. Of the 183 distributors surveyed, the great majority (143) distributed coarse sand, with 83 distributing fine gravel and 43 coarse gravel.

The majority of distributors (106 out of 183) operated their own dredges and/or barges, with 53 operating 1 vessel, 47 operating 2 to 4 vessels and the remaining 6 distributors operating 5 or more. The operator with the largest fleet operated 13 vessels. The distributors consistently relied on one extraction site for sand, but up to five different sites for the supply of gravel. The distributors reported operating 58 small boats, (0.5 to 18 Gyin; 1 Gyin = 2.83 m^3), 35 medium-sized boats (20 to 29 Gyin) and 73 (>30 Gyin) large boats for the extraction and transport of sand and gravel, with an average extraction rate of 2.3 loads per day recovering an average of 59 Gyin of material per day per operator. Sand was extracted throughout the year, with gravel extraction focused more in the dry season, presumably due to lower water levels.

The total volumes of materials being extracted from the Ayeyarwady based on the results of the survey include 5.6 million m^3 of coarse sand and 529,000 m^3 of gravel, with the distribution of extraction shown in

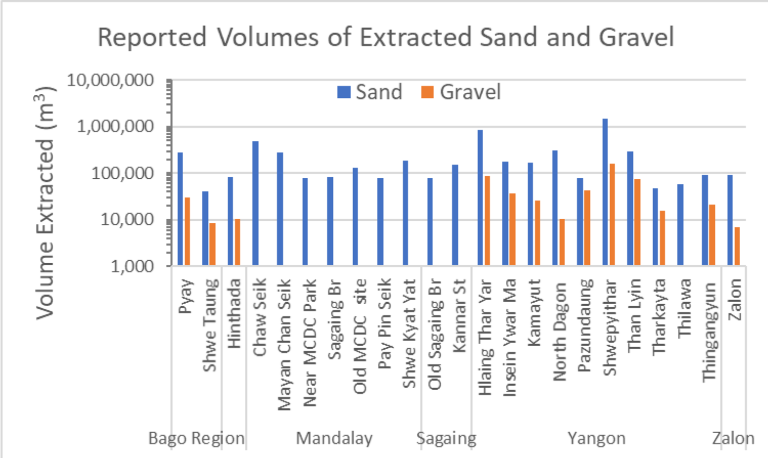


Figure 3.26. These volumes correspond to approximately 9 Mt of sand and 850,000 tonnes (t) of gravel, or ~10 million tonnes (Mt) of sediment. These estimates should be considered as indicative of minimum values for the following reasons.

- There are many distributors of sand and gravel on the river that were not included in the survey. In general, there is a sand distributor in each village along the river, and only a portion of the distributors in the major cities were surveyed. The total number of sand extractors and distributors is unknown, but it is likely that the survey included <50% of operators, estimating conservatively.
- The survey was limited to Mandalay and downstream. Upstream of Mandalay, stockpiles of sand and gravel were observed in river side villages by the SOBA 3 Team during the field investigations, indicating the total volume of material extracted from the river is considerably greater than the survey total.
- Only 63% of the sites surveyed provided estimates of the volume of material extracted. If the remaining 37% of sites extracted material at the same rates as the ones that reported, then the extracted volumes from the sites included in the survey would be of the order of ~17 Mt yr^{-1}.
- There is a risk of under reporting by operators. Extraction sites are licenced and have limits as to the volume of material that can be extracted. If these limits were being exceeded, or material was being poached by non-licenced operators, the total volume of extracted material would be higher.

Based on these factors, it is highly likely that the volume of material extracted from the river is at least twice that reported in the survey.

Distributors reported that demand fluctuated, with highest demand during the dry season and lowest during the wet season. There was no perception that the supply of coarse sand or gravel was changing, despite the closure to extraction during the wet season; 93 out of 103 distributors reported no change in the availability of coarse sand and 61 out of 65 respondents stated there had been no change to the availability of gravel. The perception regarding the demand for coarse sand and gravel was quite different, with 50% of the respondents saying there was no change to the demand for sand and 50% saying there was a decrease; however, how the number of distributors has changed over this period is unknown, so it is difficult to interpret these impressions. Similarly, for gravel, 58% of the distributors reported no change to demand, with the remainder suggesting there was a decrease.

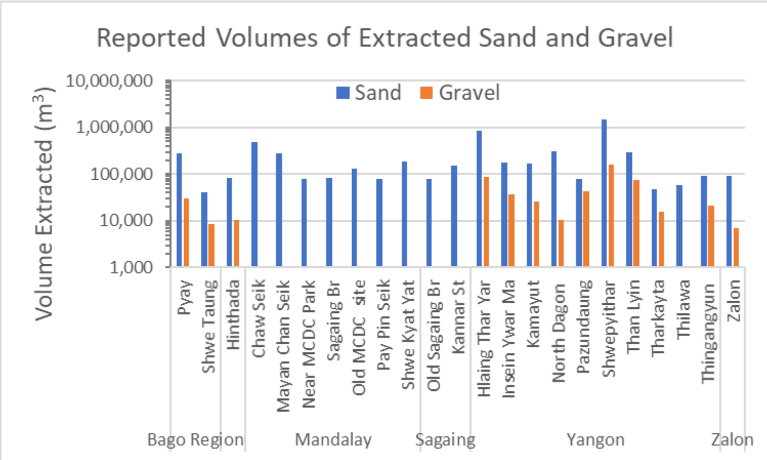


Figure 3.26 - Summary of volumes of sand and gravel extracted from different areas based on the survey results

3.5.2 Sediment extraction in the upper Ayeyarwady

A survey of material extraction from the upper Ayeyarwady was not completed, but field observations provided an indication of the scale and extent of sediment usage in the area around Myitkyina. Along the riverbank upstream of Myitkyina there were multiple sediment extraction sites with stockpiles of gravels (<65 mm) and cobbles (>65 mm). The use of coarse gravels and cobbles in the construction of bank protection was evident along the length of the town's waterfront, with kilometres of banks already reinforced using river rounded cobbles, and long lengths of additional banks undergoing protection

measures at the time of the field work (

Figure 3.27). In addition to the large-scale municipal use of gravels and cobbles for bank protection, many houses had fences constructed of gravels and piles of river-derived material located near their dwelling, presumably stockpiled for future construction uses.

The ubiquitous use of this coarse material reflects its availability in the river, where it is derived from the steep headlands. After travelling south from Myitkyina to Bhamo, the SOBA 3 Team did not see widespread use of river cobbles, suggesting the coarse material is not transported as large clasts long distances downstream.

Figure 3.27 - Photos of gravels extracted from the river and the use of gravels in the construction of bank protection measures in Myitkyina, and for fences at private homes

3.5.3 Geomorphic implications of sand and gravel extraction

The geomorphic impact of coarse sand and gravel extraction is difficult to accurately evaluate due to the lack of recent, accurate suspended and bedload sediment measurements or annual budgets to provide a context within which to interpret the extraction rate. Estimates of suspended sediment transport in the Ayeyarwady range from ~240 Mt yr^{-1} (Milliman and Syvitski, 1992) to ~340 Mt yr^{-1} (Robinson et al., 2007). The coarse sand and gravel sediment components extracted from the Ayeyarwady would predominantly be transported as bedload. Bedload transport is not included in the above estimates, but typical estimates of bedload transport generally range from ~2% to 20% of the suspended load depending on the concentration and grain-size of the material being transported (Maddock and Borland, 1950). Applying a bedload range of

3 to 10% to the estimated suspended sediment loads suggests that 7.2 Mt yr^{-1} to 34 Mt yr^{-1} of material is transported as bedload.

Compared to these rates, the minimum estimate of 10 Mt per year of extracted material from the survey results could represent between ~30% to 100% of the estimated bedload. Assuming the volume of material removed is at least twice the volume recorded in the survey due to the aforementioned reasons, the volume being removed could represent more material than is transported as bedload each year. Removing this magnitude of material from the sediment budget will have local and distal geomorphic impacts.

The closing of extraction sites during the 2017 wet season due to the communities' concerns regarding bank erosion indicates that there is the perception, if not demonstrated causation, between extractive activities and local bank stability. The investigations undertaken by local Government and DWIR should provide insights and a baseline against which future channel and bank changes can be gauged.

Based on media reports, communities in the Bago region attribute the extraction process as well as the volume of material extracted as causes for increased bank instability. The residents have observed that large volume of fine-grained material are disturbed and re-distributed in the process of extracting the coarser sands and gravels, and these changes alter the river currents around mid-stream islands, promoting increased bank erosion[3]. Other drivers such as climate change, deforestation and terrestrial mining activities have been identified as altering the flow and sediment loads in the river leading to an increase in flooding and bank erosion[4]).

Recent investigations into the stability of the delta front by Anthony et al., (2017a) are also relevant to this issue. The delta investigation has collected evidence suggesting that the resilience of the delta may be decreasing, especially around the areas where the distributaries discharge to the sea, which forms the transition zone between terrestrial and coastal. The investigators recorded an erosional trend in this region of the delta, which is discussed further in Section 6.2. It is unknown if there is a direct link between the present level of extractive activities, river channel changes and changes to the delta front. However, there is a high risk that if the volume of material extracted from the river is of a similar magnitude to the volume that has historically been delivered to the delta front, sediment starvation of the delta will eventually occur.

Bank erosion is a complex process and establishing a direct link between the timing, locations, and volumes of material extracted and geomorphic changes will always be difficult. However, obtaining accurate information about the magnitude of suspended and bedload transport at different points in the river, and accurately recording the types and volumes of material being extracted are necessary first steps in understanding and quantifying the issue.

[3] http://www.elevenmyanmar.com/local/11128
[4] https://frontiermyanmar.net/en/is-yearly-flooding-the-new-normal

Table 4 - Summary of the locations, numbers of operators, and material extracted as determined by the SOBA 3 Sand and Gravel Mining Survey conducted between 26 July and 19 August 2017

Region or district	Township or ward	Number of surveys completed	Average length of operation (yrs)	Number distributing coarse sand	Number distributing small gravel (~2 to 30 mm)	Number distributing large gravel (~30 to 65 mm)	Volume of construction sand sold (m^3)	Volume of gravel sold (m^3)
Ayeyarwady	Danubyu	4		4	2		0	0
	Nyaung Done	3	2	1	1		0	0
		7		**5**	**3**			
Bago Region	Pyay	5	14.75	5	5		284,062	30,564
	Shwe Taung	3	11	2	2	2	41,318	8,490
Total		**8**		**7**	**7**	**2**	**325,380**	**39,054**
Danubyu	Danubyu	1	37	1	1		0	0
		1		**1**	**1**			
Hinthada	Hinthada	5	3	5	4		82,637	10,188
Total		**5**		**5**	**4**		**82,637**	**10,188**
Mandalay	Chaw Seik	12	9.7	9			493,750	0
	Mayan Chan Seik	6	10	6			272,699	0
	Near MCDC Park	1	1	1			77,471	0
	Near New Sagaing Bridge	1	2	1			83,658	0
	Old MCDC Dumping site	1	1	1			129,119	0
	Pay Pin Seik	8	7	1			77,471	0
	Shwe Kyat Yat	4	10	2			185,931	0
	Shwe Sar Yan Village	4	3.8	3	4		0	0
Total		**37**		**24**	**4**		**1,320,099**	0
Sagaing	Near Old Sagaing Bridge	1	3	1			77,471	0
	Sagaing Kannar Street	2	17.5	2			154,943	0
		3		**3**			**232,414**	
Yangon	Hlaing Thar Yar	30	7.4	27	18	4	864,000	86,685
	Insein Ywar Ma	8	12.6	7	6	5	180,768	36,904

Region or district	Township or ward	Number of surveys completed	Average length of operation (yrs)	Number distributing coarse sand	Number distributing small gravel (~2 to 30 mm)	Number distributing large gravel (~30 to 65 mm)	Volume of construction sand sold (m³)	Volume of gravel sold (m³)
	Kamayut	8	10.5	5	3	3	165,272	25,470
	North Dagon	7	10	4	2	2	304,721	10,188
	Pazundaung	4	8.5	4	4		77,471	43,355
	Shwepyithar	36	8.8	30	18	16	1,479,693	157,205
	Than Lyin	12	5.6	9	9	9	299,557	76,693
	Tharkayta	4	5.3	3	2		46,483	15,494
	Thilawa	2	1.5	2			56,671	0
	Thingangyun	2	20.5	2	2	2	92,965	21,197
Total		**113**		**93**	**64**	**41**	**3,567,601**	**473191.25**
Zalon	Zalon	9	1.5	9			92,966	6,792
Grand Total		**183**	**8.7**	**144**	**83**	**43**	**5,621,097**	**529,225**

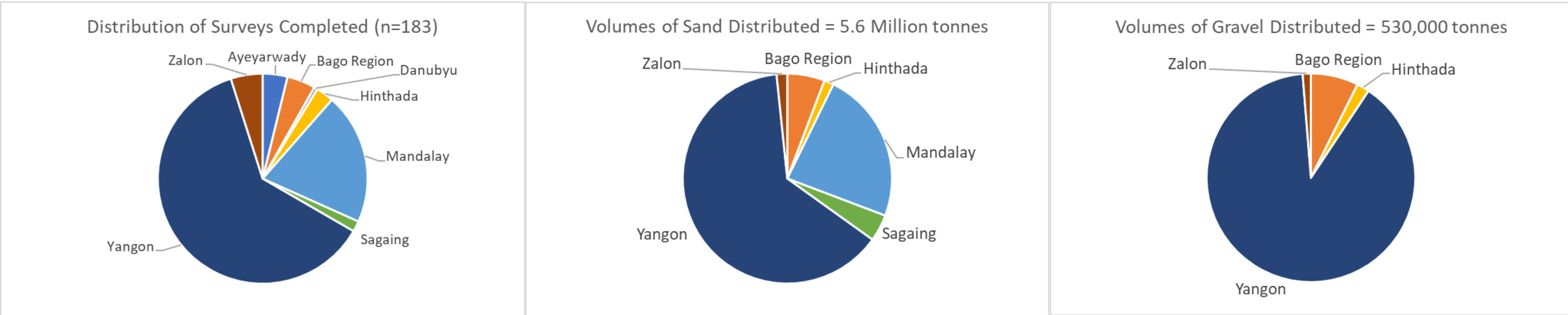


Figure 3.28 - Pie charts showing (left) distribution of where surveys were completed (centre) sand distribution by district (right) gravel distribution by district.

3.6 Dredging

Dredging is aimed at altering the morphology of river channels to achieve a desired management outcome. These local changes can have the same impacts as those related to sand mining, with impacts propagating both upstream and downstream (see Section 3.4). Dredge spoils deposited within the channel can alter the hydraulics at the disposal site and initiate additional channel changes. One difference between sand mining and dredging is that dredging moves or removes all grain-sizes located in the target area, whereas sand and gravel mining targets specific grain-size fractions.

Dredging is often accompanied by the installation of river engineering works, such as groynes, that are aimed at maintaining the post-dredging condition of the river. This infrastructure can alter the geomorphology of the river locally and downstream, such as where groynes retain sediment locally but enhance downstream erosion.

Dredging in the Ayeyarwady has been planned and managed by DWIR since 1972. The agency undertakes dredging for the following management objects (DWIR, 2016):

- protect the riverbanks from erosion;
- cooperate with other organizations in demarcation of danger water level of the towns;

utilize the river water for domestic and agriculture all the year round (

- Figure 3.29);
- protect bank erosion of border rivers;
- observe the long-term existence of the cross-river bridges by river engineering point of views;
- manage the prevention of river water pollution; and
- maintain adequate depth for maximum loading capacity of the vessels (DWIR, 2016).

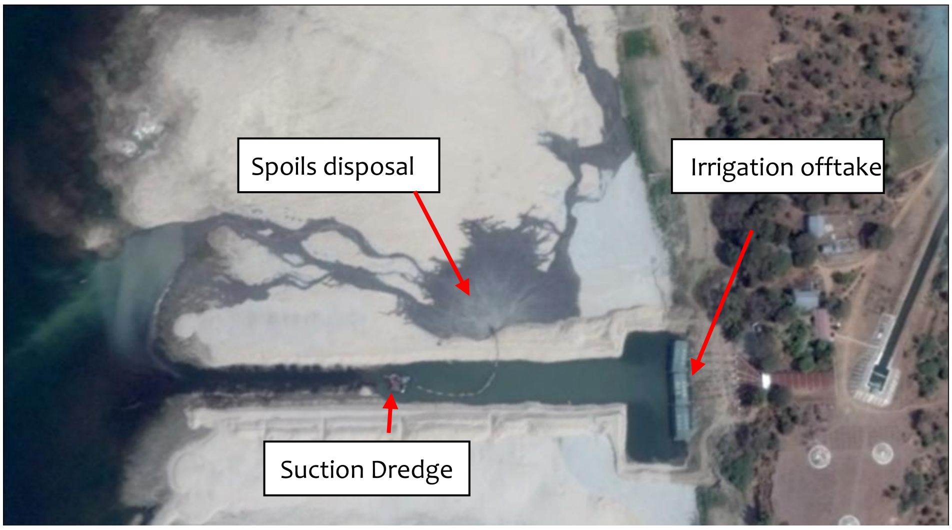


Figure 3.29. Dredging at Yeosin Creek to maintain access to Ayeyarwady for the extraction of water for irrigation. Suction dredge is depositing spoils on adjacent sand bank

Dredging in the Ayeyarwady is conducted using either back-hoe style dredges, which extract material and deposit it onto barges for subsequent disposal, or cutter suction dredges that excavate and remove sediment by suction. The pumped slurry is transported to a disposal site by pipelines (DWIR, 2016). Disposal sites can be located either in the river channel, typically several hundred metres from the dredge site, or onshore. An example of a dredging plan for the Ayeyarwady near Nyaung Oo (

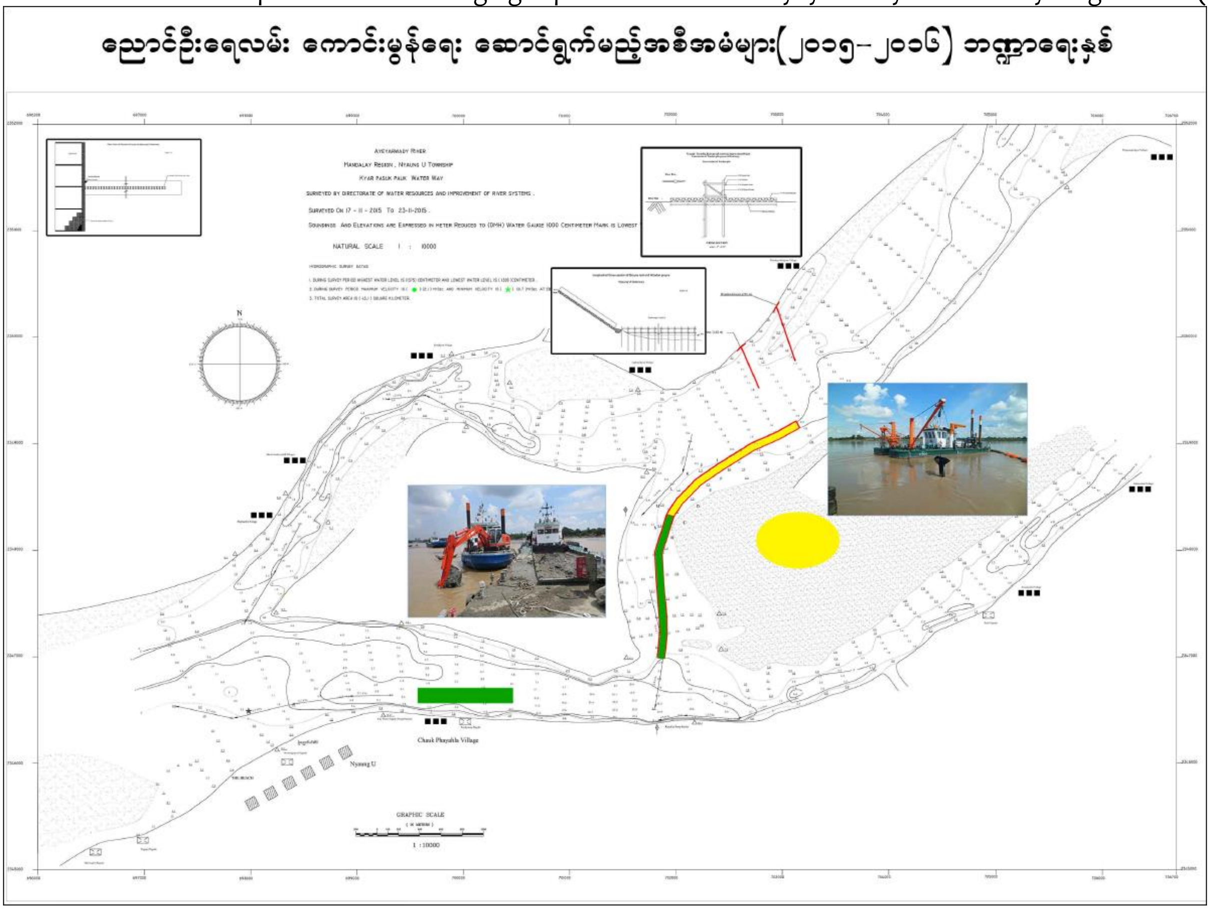


Figure 3.30) shows the target dredging area, the type of dredges used in each area, and the location of the dredge spoil disposal sites for each type of dredging.

In a proposal to conduct micro-projects in the middle Ayeyarwady, DWIR (2016) states that

> *'no geomorphology or sediment studies have been conducted or models applied prior to the designs. The works are considered to be dynamic, temporary and reversible… in line with historical seasonal dredging and groyne construction undertaken by DWIR since 1972 and the World Bank Environmental and Social Safeguards.'*

The agency now includes social and environmental considerations in the development of dredging plans, and presumably under AIRBM this will expand to include local and upstream/downstream geomorphic considerations as well.

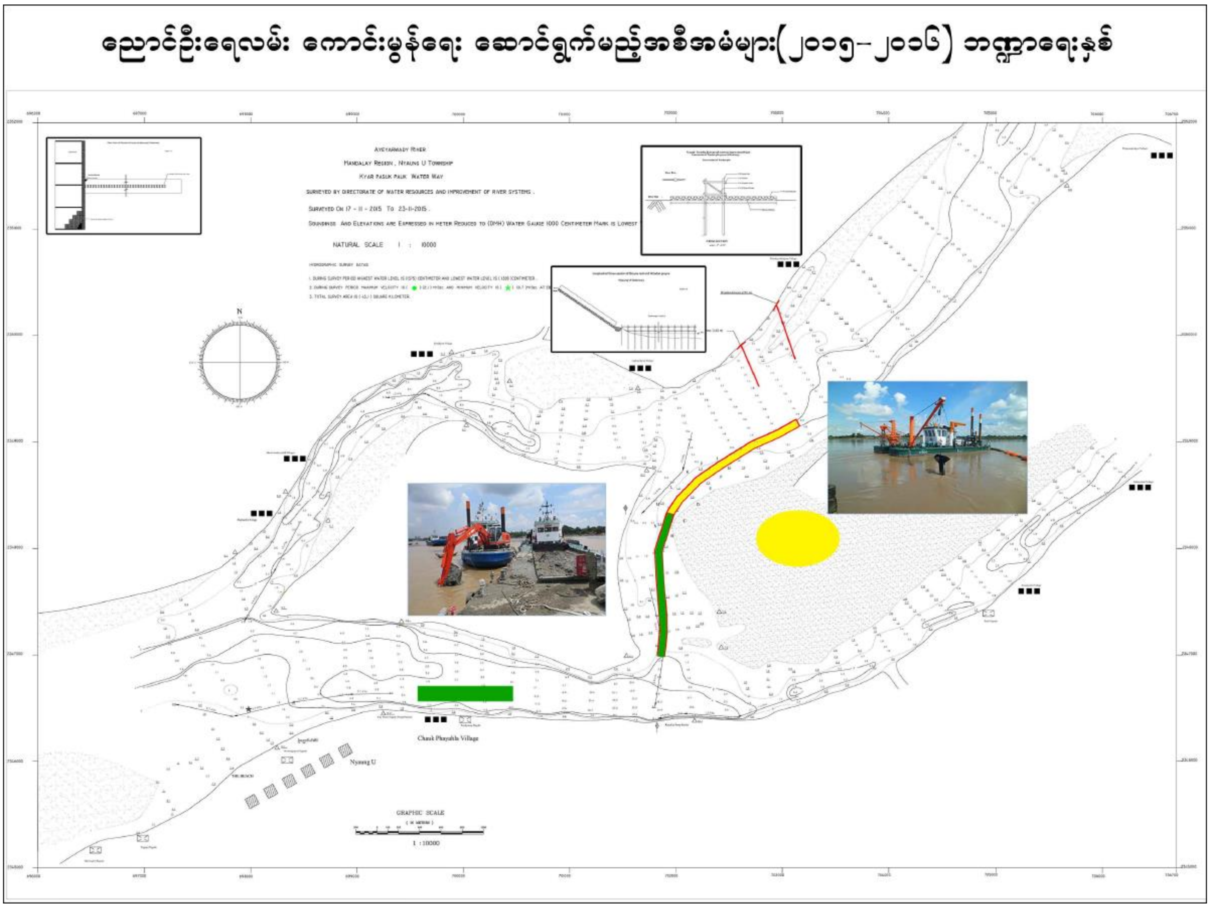


Figure 3.30. Dredging map for maintenance of navigation channel near Nyaung-Oo. ***Area outlined in red indicates dredging target, with the yellow area to be dredged using a cutter suction dredge and green area with a back-hoe dredge. The disposal area for each spoil type is indicated in yellow and green, respectively***

3.6.1 Distribution and volumes of dredged material

DWIR (2016) estimates that from 1989 to present, 24 million m^3 of sediment has been dredged in the Ayeyarwady. Information provided by the DWIR for the period of 2012 to 2017 is summarized by year and district in **Error! Reference source not found.** to provide an overview of recent dredging activities in the Ayeyarwady. The total volume of material dredged between 2012 and 2017 was 7.72 Million m^3 (approximately 12.4 Mt), equivalent to about one-third of the total dredged since 1989. Most (78%) of the dredging has occurred since 2015, with dredging effort predominantly directed at the middle and lower river (78% in Mandalay, Magwe and Ayeyarwady). The highest dredging volumes were reported in 2015, with 2.5 million m^3 of material dredged from the river. This value is considerably lower than the estimated volumes of material removed through sand and gravel mining, which are at least ten-fold higher. However, because dredging is frequently aimed at altering the morphology of the river channel such that flow hydraulics are altered, it may have a proportionately greater impact on the geomorphology of the river per volume of material removed, as compared to sand and gravel mining.

The 2012 to 2017 dredge volumes grouped by management objective (

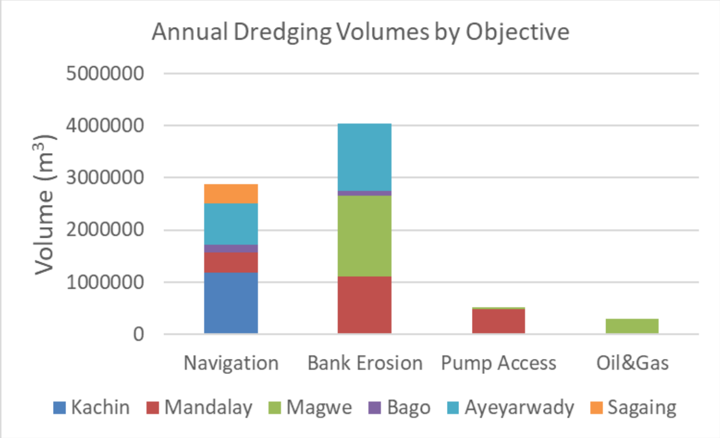
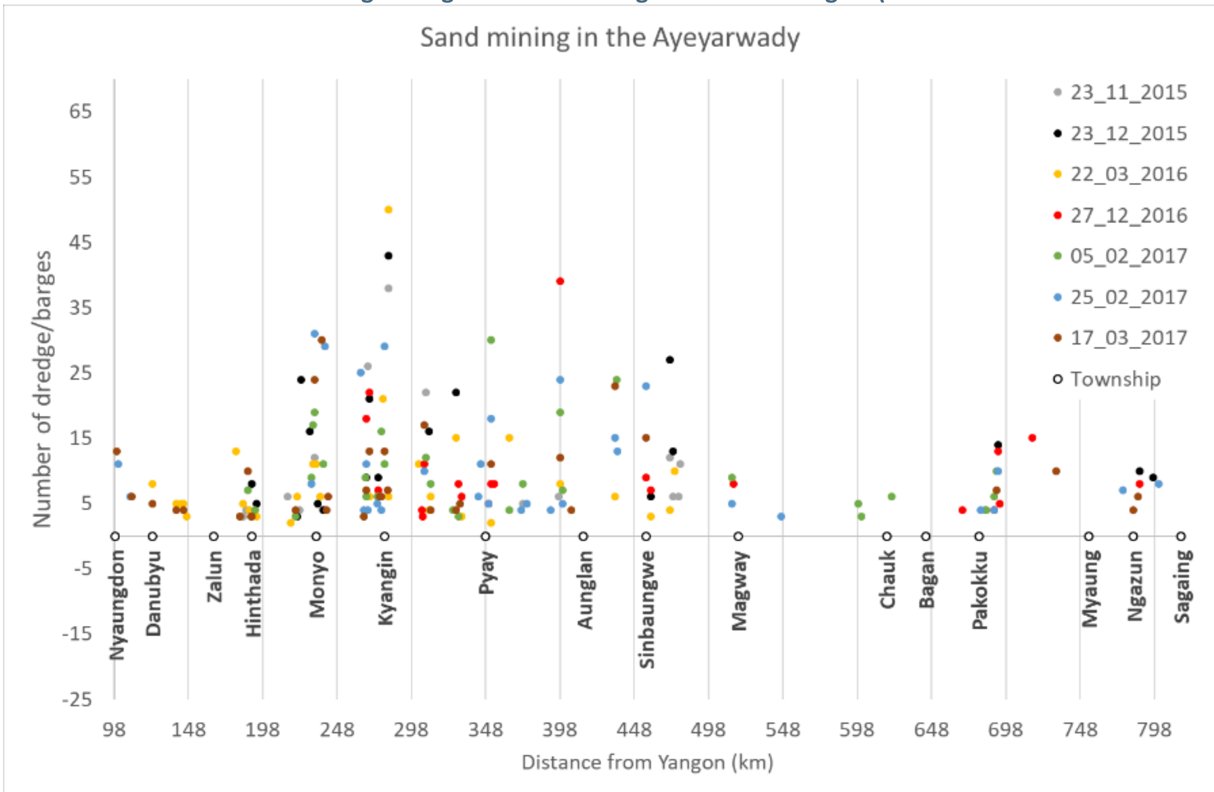


Figure 3.32) demonstrate that most dredging projects aim at the management of bank erosion and maintenance of navigation channels. Dredging for bank erosion predominantly occurs in the middle and lower Ayeyarwady, in the Mandalay, Magwe and Ayeyarwady Regions, while dredging for navigation occurs throughout most of the river. Interestingly, in the Magwe Region, no dredging projects are reported for navigation, but the region has the highest volume of dredging associated with bank erosion management, with dredging recorded for this purpose from 2015 to 2017, but not prior. The satellite image analysis of sand and gravel mining activities in the Ayeyarwady found a large number of dredgers operating in the Magwe Region between Magwe and Sinbaungwe (



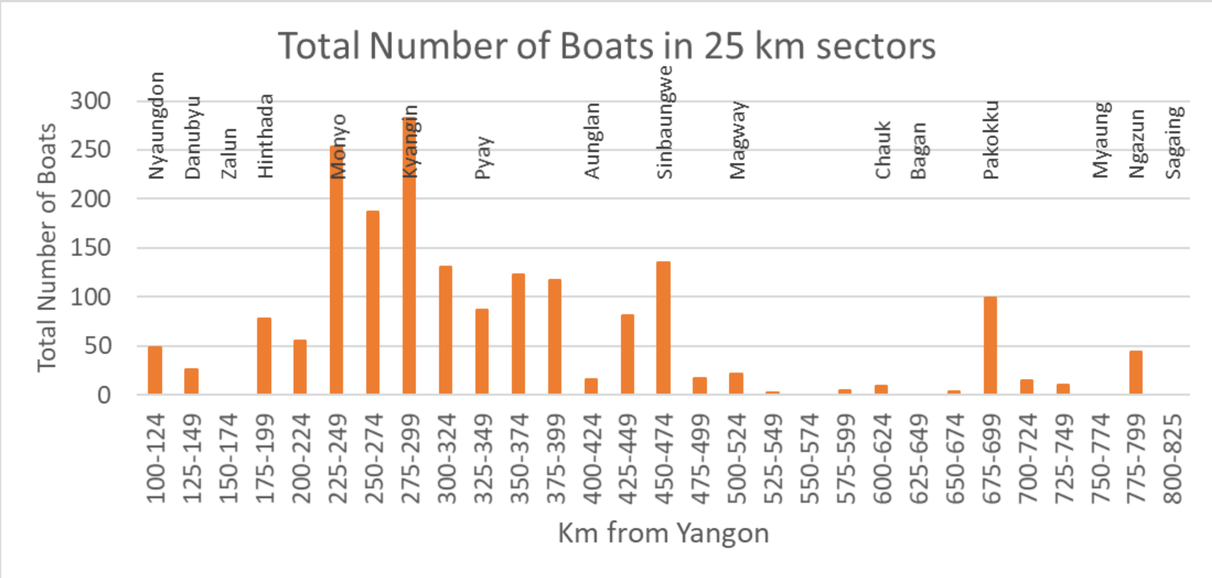
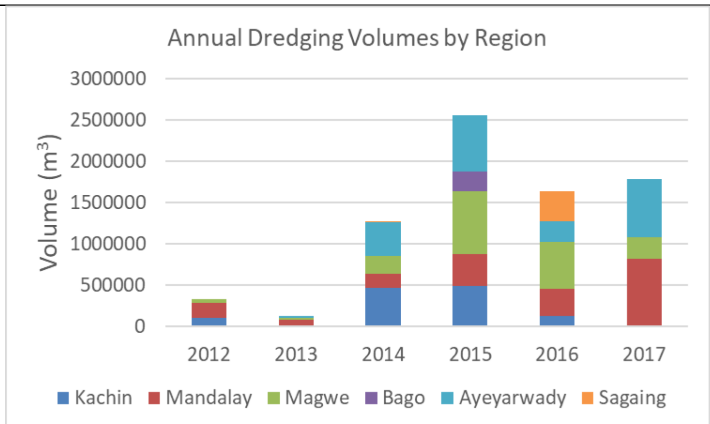


Figure 3.20). Over the past few years, sand and gravel mining may have resulted in the deepening of channels that is leading to an increase in bank instability. This is only a hypothesis, and additional investigations would be required to evaluate this potential linkage.

Much smaller volumes are extracted to maintain 'pump' access to the Ayeyarwady for the provision of irrigation supply, with most of the works occurring within Mandalay Region. Dredging to maintain access to the Thanbyakan Petrochemical Complex at Minhla was reported for 2013 to 2015 in the Magway region.



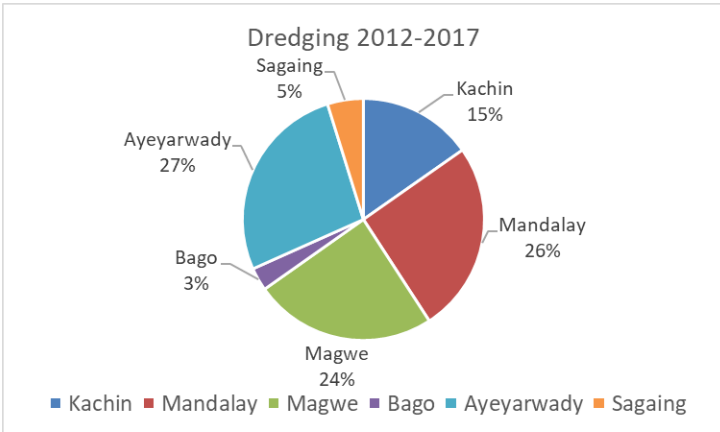


Figure 3.31. (left) Administrative regions of Myanmar (right top) Annual dredge volumes by district and (bottom) distribution of dredging between districts between 2012 and 2017 (DWRI).

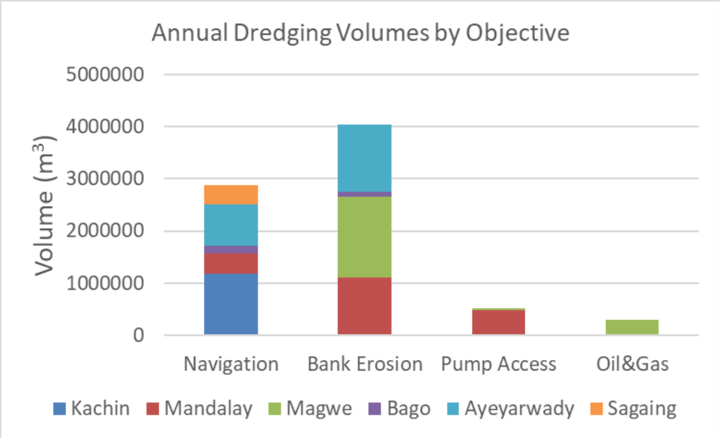


Figure 3.32. Dredging volumes extracted 2012 – 2017 grouped by management objective. Source: DWIR.

3.7 Other Land and River Use Activities

Numerous other land use activities affect sediment transport and river geomorphology. The following activities have not been investigated in the Ayeyarwady in detail, but based on the experience from other river basins should be considered in overall catchment management and development.

3.7.1 Road construction

Road construction can affect river systems in several ways. Road bases may be elevated and function as levees, and thus limit the connectivity between floodplains and river channels. If flow is prevented from accessing floodplains, then river levels and water velocities can increase, potentially increasing downstream flooding and/or increasing erosion risks.

Roads constructed on hill slopes affect rivers by directly increasing sediment input during the construction phase, and by altering hillslope stability. Hillslope erosion has been linked to high sediment inputs in the Lancang River basin in China, even in areas of low population density (

Figure 3.33; Bravard et al., 2005). Sediment 'waves' generated by road construction can take years to transit through the river system, altering the channel morphology, bed elevation and hence energy of the river many kilometres from the road site (Bravard et al., 2005).

Along the main stem of the Ayeyarwady, there are few locations where roads are located on steep slopes parallel to the river, so the direct input of sediments from roads poses a low risk. However, in the headwater catchments, and in the tributaries, roads are commonly located on steeper slopes of river valleys and contribute to sediment input. The location of roads within mining affected areas can compound these impacts, as can other activities, such as firewood harvesting, overgrazing or poor agricultural practices (Bravard et al., 2005).

Figure 3.33- (left) impacts of road construction on steep-slopes (right) sediment input from road construction has been re-worked during a flood event, resulting in dissected river terraces

Figure 3.34 - Hillslope erosion in the Shweli River catchment associated with road placement and other land use activities

3.7.2 Floodplain developments and channel engineering

Floodplain developments affect the hydrology and geomorphology of river systems. Floodplain infrastructure that restricts water accessing floodplains reduces floodplain inundation and sedimentation, and results in higher water levels and water velocities within river channels. Collectively, these changes reduce the productivity of the floodplain and induce increased erosion of the river channel. The removal of floodplain vegetation, or conversion to crops can also reduce the effectiveness of floodplains to mitigate flooding, due to a reduction in the roughness of the floodplain promoting higher flow velocities (Freeman et al., 1994). If large areas of floodplain are removed from river systems the risk of downstream flooding is increased, as floodwaters are no longer able to be temporarily stored on the floodplains. A reduction in floodplain capacity will also reduce the potential for the slow release of water back into the river channel during the recession of floods.

Engineering structures aimed at stabilising the river channel and/or protecting shore based assets may be locally effective, but frequently increase downstream impacts due to the transference of water and river energy. For example, in some areas of the Mississippi River in the United States, it has been found that for each 1 km of levee system constructed along the river, the downstream river stage is increased by about 2 cm (Freeman et al., 1994). This is particularly relevant in the Ayeyarwady as the river has few hydraulic controls, and the transference of energy can have impacts over long distances resulting in increased bank erosion and/or channel incision. Once these impacts occur, they can develop feed-back loops through which deeper and steeper channels lead to increased flow velocities that in turn increase erosion and channel incision.

3.7.3 Boat wakes

A potential contributor to bank erosion in the Ayeyarwady is the impact of boat wakes on the sandy banks. Boat wakes differ from wind driven waves in that the wave period is typically longer. Longer periods result in the wave motion being felt deeper in the water column, and water velocities at depth are higher as compared to a wave with the same amplitude but shorter wave period (Gourlay, 2011).

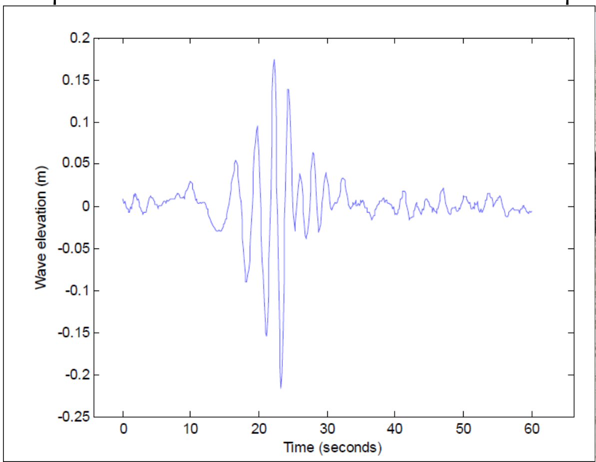


Figure 3.35 shows a typical wave profile for a boat wake, showing the change to water level and depth of impact, and an example of a sandbank that would be highly susceptible to erosion. The wave period in combination with the slope of the bank can also affect what type of wave strikes the bank, e.g. spilling, plunging to surging. Boat wakes can also erode banks indirectly, through the erosion of vegetation, which is accustomed to resisting impacts from wind driven waves (Gourlay, 2011).

The banks that are susceptible to boat-wake induced erosion would also be susceptible to scour during high flows. However, boat wakes have the potential to erode this material during periods of low flow, and thus accelerate the overall rate of bank erosion, with new material being exposed and scoured at high flow. Boat wakes also have the potential to re-suspend sediment and increase turbidity, which can affect riparian and riverine ecosystems. Wave induced erosion has been identified as a contributor to bank erosion in many rivers of the world (Bilkovic et al., 2017).

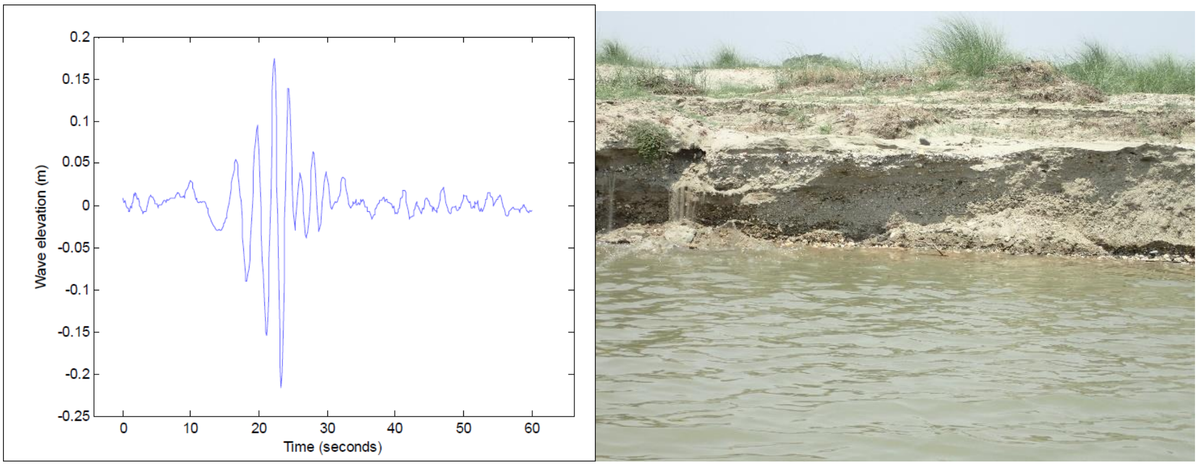
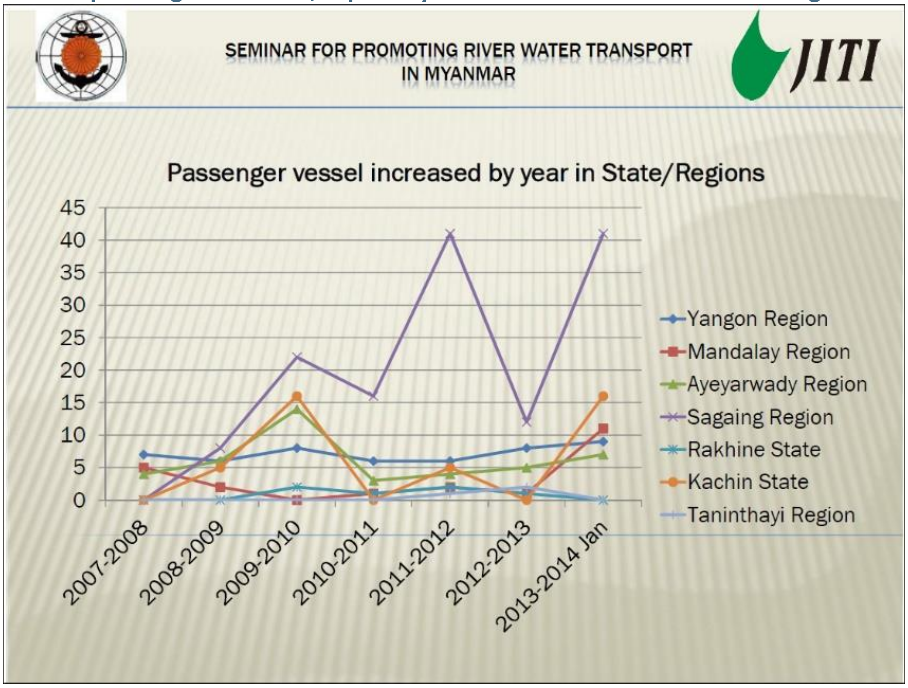


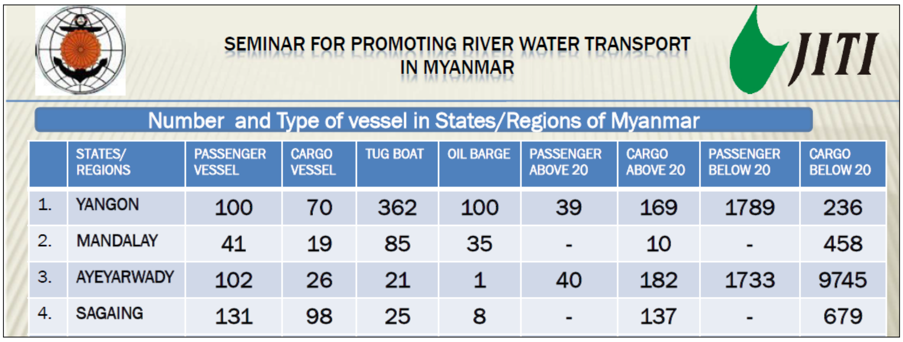
Figure 3.35 -(top) Wave profile for a small craft on an Australian River (Source: Gourlay,2011); (bottom) photo of river bank susceptible to wave erosion

The size and energy associated with boat wakes is a function of the vessel length, water depth, channel shape and boat speed (Bilkovic *et al.,* 2017). Large vessels, such as barges, that do not plane tend to generate large boat wakes as they displace large volumes of water as they travel.

In the Ayeyarwady, there has been a decrease in the volumes of cargo transported by ship on the river, and in the number of passengers using ferry services (ICEM, 2017). However, there has been a large increase in the number of tourist vessels operating in the river, especially in the alluvial reach between Mingun and

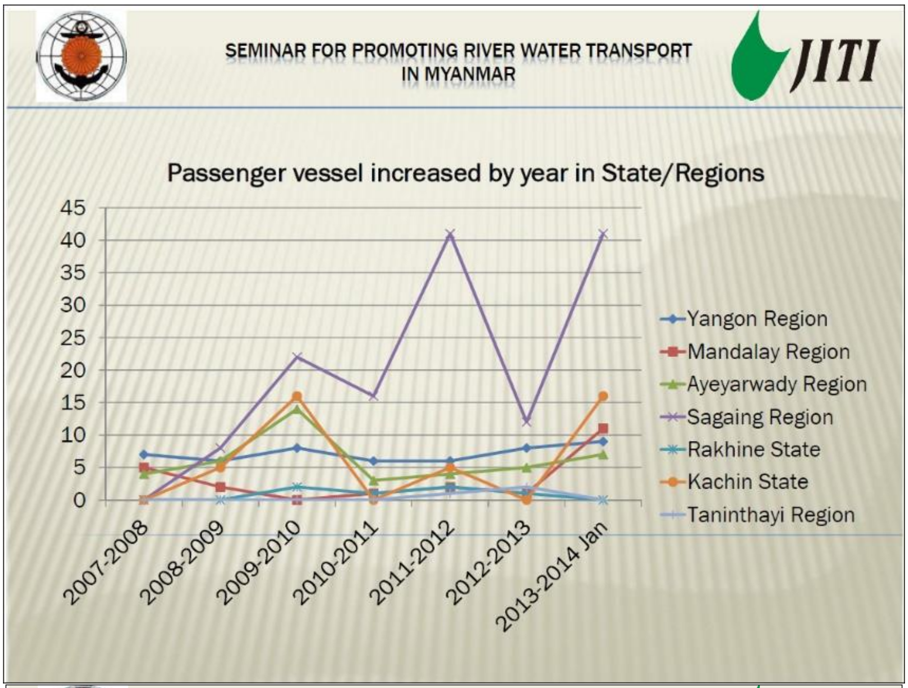


Old Bagan, as shown in



	STATES/ REGIONS	PASSENGER VESSEL	CARGO VESSEL	TUG BOAT	OIL BARGE	PASSENGER ABOVE 20	CARGO ABOVE 20	PASSENGER BELOW 20	CARGO BELOW 20
1.	YANGON	100	70	362	100	39	169	1789	236
2.	MANDALAY	41	19	85	35	-	10	-	458
3.	AYEYARWADY	102	26	21	1	40	182	1733	9745
4.	SAGAING	131	98	25	8	-	137	-	679

Figure 3.36. These vessels operate predominantly in the dry season, when boat wakes could have a large impact on the exposed riverbanks.



SEMINAR FOR PROMOTING RIVER WATER TRANSPORT IN MYANMAR

JITI

Number and Type of vessel in States/Regions of Myanmar

	STATES/ REGIONS	PASSENGER VESSEL	CARGO VESSEL	TUG BOAT	OIL BARGE	PASSENGER ABOVE 20	CARGO ABOVE 20	PASSENGER BELOW 20	CARGO BELOW 20
1.	YANGON	100	70	362	100	39	169	1789	236
2.	MANDALAY	41	19	85	35	-	10	-	458
3.	AYEYARWADY	102	26	21	1	40	182	1733	9745
4.	SAGAING	131	98	25	8	-	137	-	679

Figure 3.36 - (top) Passenger vessel increase by year in Myanmar. *Yangon, Mandalay, Ayeyarwady and Sagaing are located within the Ayeyarwady River Basin* (bottom) registered vessels in States/Districts in Myanmar. (*Source: Myint Thien, 2014)*

4. SEDIMENT TRANSPORT AND CHARACTERISTICS

4.1 Review of Existing Data

Daily time series of sediment discharge (in kilograms per second) have been provided for seven monitoring sites. The data is based on flow-sediment relationships at each site. These relationships are uniform over time, as there has been no adjustment to the sediment rating curve applied to the ~30 years of results (

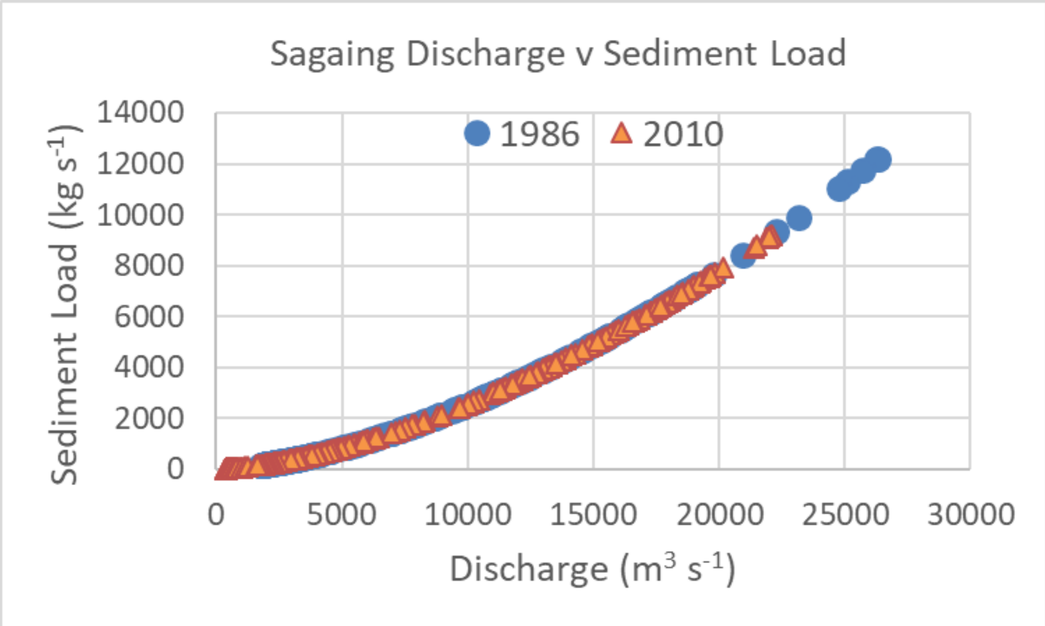


Figure 4.1). It is virtually impossible that the relationship between flow and sediment transport has not been altered over the past three decades, given the land use and river flow changes that have occurred during this period (Furuichi, et al., 2009). An example of the variability that is commonly recorded in rivers is shown in

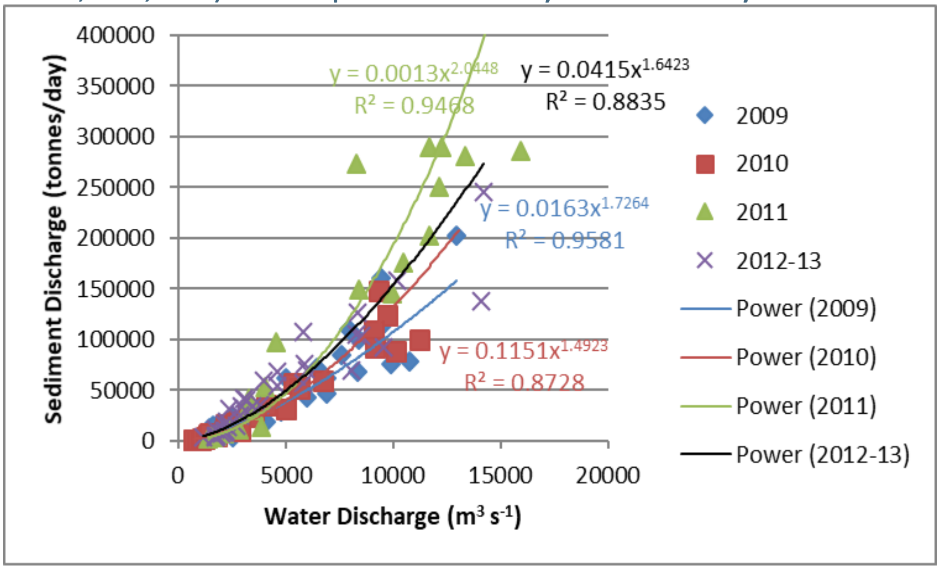


Figure 4.2, with rating curves from a site in the Mekong River showing large differences between years. Data collected in 2011, which was a high-flow year show that sediment loads associated with 10,000 m^3s^{-1} flows were approximately 200,000 t day^{-1}, whereas similar flows in 2009, a relatively dry year, transported sediment loads of only half this total (~100,000 t day^{-1}).

The relationships between the sediment discharge and the flow regime could provide a useful historic perspective, if additional information relating to the dataset were available to answer the following questions.

- What is the source of the original information used to derive the sediment rating curve?
- If based on data, over what time frame were the original data collected?
- What was the monitoring frequency of the original data collection period?
- What suspended sediment sampling method was used?
- Who completed the data collection and analysis and what was the aim of the investigations?
- What laboratory method was used to determine the suspended sediment concentrations and what was the minimum sediment size captured by the analysis?

It is recommended that an effort be made to locate this additional dataset and any meta-data that may exist describing when and how the relationships were derived.

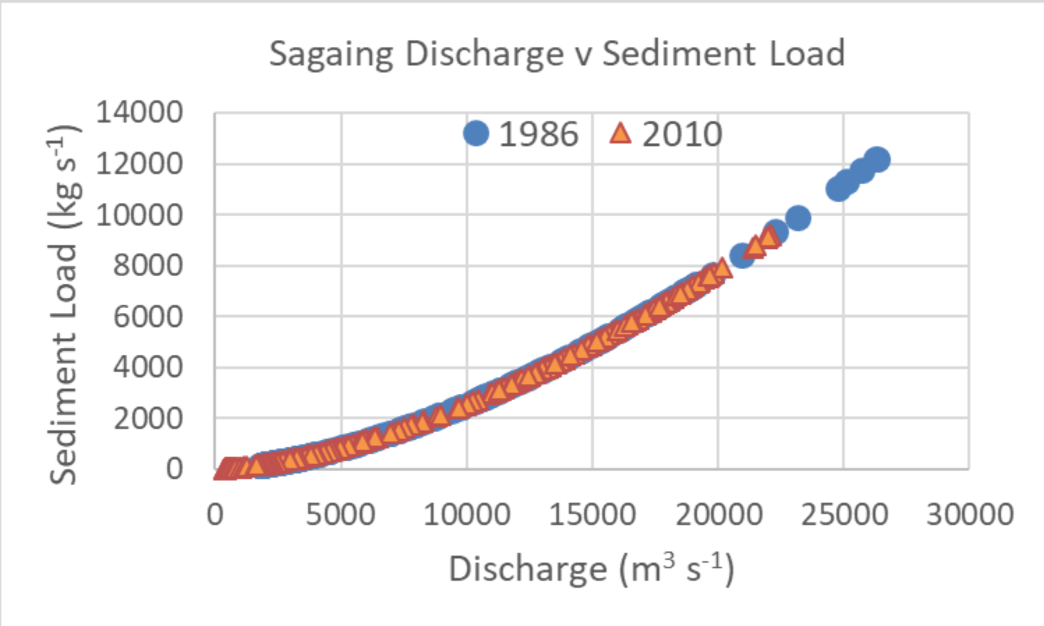


Figure 4.1 - Comparison of sediment loads at Sagaing in 1986 and 2010. Results demonstrate that the same algorithm has been used over the period of monitoring record. (Data provided by DMH)

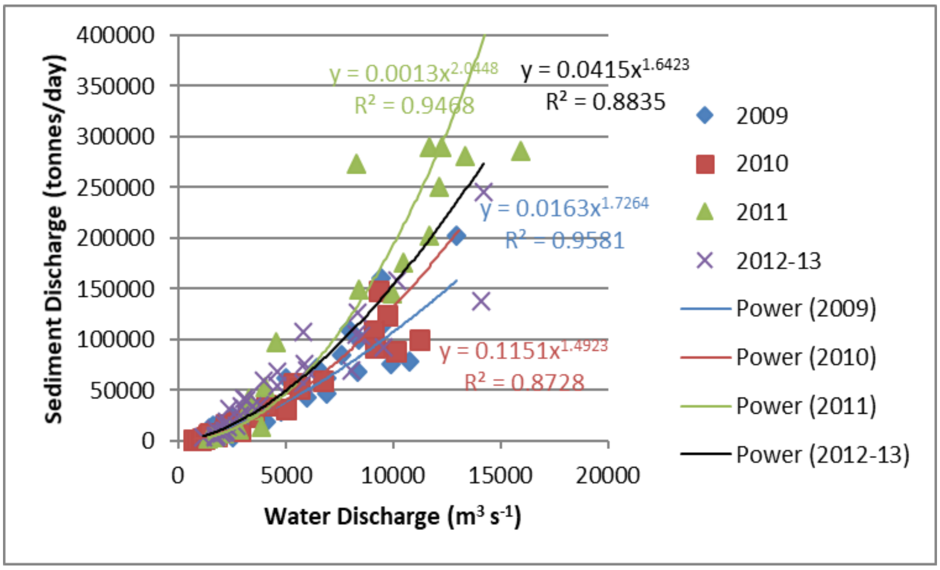


Figure 4.2 - Sediment rating curves from 4 years in the Mekong River. Curves show variability due to sediment trapping in upstream dams, different hydrologic conditions (e.g. 2011 was a flood year) and changes to upstream land uses (Koehnken, 2015).

In addition to the questions associated with the derivation of the sediment rating curves, other work completed under SOBA Activity 1 (Walker, 2017) has documented deficiencies in the accuracy of the water discharge rating curves used to determine the water flow in the Ayeyarwady. Because the calculated sediment loads are based on these flow records, any errors in discharge will translate into errors in the sediment load estimations, compounding the concerns associated with using the historic data.

The relationship between sediment supply and transport does not remain static, and sediment rating curves need to be continually revised to provide accurate results. As a rule of thumb, a minimum of at least 20 depth and cross-section integrated samples should be collected over the course of each year, with sampling skewed towards periods of high discharge and sediment transport (e.g. monsoon season), with sediment rating curves derived for each year independently. If multiple successive years show similar trends, these results can be combined to provide a rating curve for a specific period, but cannot be applied to other time-periods without sampling results that confirm a similar relationship. Sediment rating curves are inherently more susceptible to change as compared to discharge rating curves because natural processes such as land slips or other episodic events (earthquakes, floods, and droughts) and land use activities (forestry, agriculture, mining, road construction, hydropower, and irrigation development, etc.) interact to continually alter the quantity of sediment available for transport, and when and how the material enters the waterway.

For these reasons, the existing dataset has very poor reliability, and cannot be used to provide an accurate picture of the status of sediment transport in the river. Importantly, it is also suggested that these data should not be used, as bad data is frequently worse than no data as it can lead to an erroneous understanding of situations and processes that are then used as the basis for management decisions.

This critique is not a criticism or a reflection of the talented and dedicated people working in the fields of hydrology and sediment transport in Myanmar, the groups that have been instructed to interpret these data, or the existing systems with respect to sediment monitoring or data management. Sediment monitoring is difficult, expensive, and time consuming, which often makes it a low priority compared to other national needs, especially in a developing country facing innumerable challenges, such as Myanmar. Recognising and discussing the shortcomings is the first positive step towards addressing the issues to arrive at an improved sediment monitoring system in an integrated and cost-effective manner. A discussion of future monitoring approaches and a recommended strategy is presented in Section 6.

In the short period allocated for the SOBA 3 project, the team has attempted to collect field information that provides insights into sediment transport and geomorphic processes. The remainder of this chapter presents the findings of these investigations.

4.2 Field Investigations

4.2.1 Overview of field activities

The SOBA 3 Team conducted a field expedition between 24 April and 10 May 2017. The field work included site visits to the Ayeyarwady River from upstream of the confluence of the Mali and N'mai Hka Rivers, to the head of the delta near Danubyu. The investigations from the headwaters to the top of zone Q were conducted by boat, with the exception of an approximately 150 km river reach downstream of Myitkyina and upstream of Bhamo, which was not able to be accessed due to logistical and security reasons. The majority of the field work, extending from upstream of Bhamo to approximately 15 km downstream of Pyay was conducted using a large live-aboard vessel (RV Mingun) and a smaller work boat that allowed access to the banks and sandbars in the river. Sites investigated upstream and downstream of this reach, including the headwater area, the Ayeyarwady upstream and downstream of Myitkyina, and areas in the delta, were visited using locally contracted small boats.

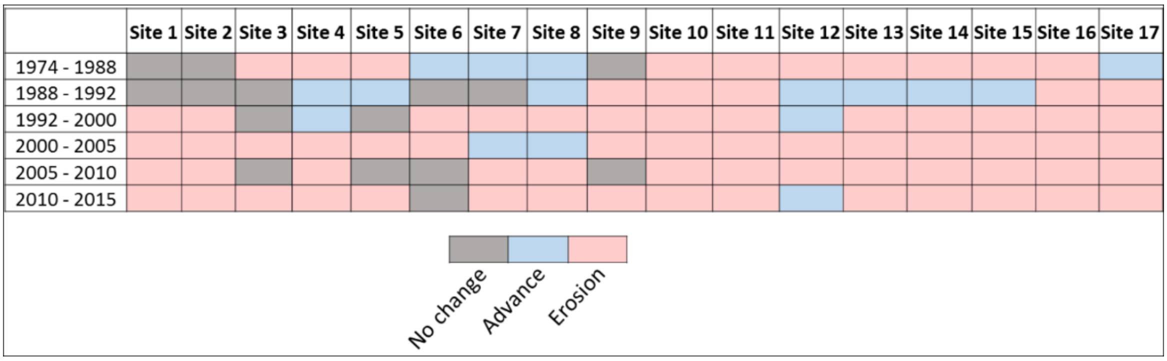
Due to the long distance of river investigated over a relatively short period of time, only a limited number of stops were able to be completed in each geomorphic zone. The SOBA 3 Team prioritized data collection in alluvial dominated reaches, especially those in which navigation or bank stability had been previously identified as issues.

The field work included the following components:

- Field observations — The boat-based investigations allowed the continuous observance of the channel form, sediment types and distribution, valley characteristics, and local land uses that can affect geomorphic processes. The elevated deck on the live-aboard vessel provided a view of the banks and the floodplains.

Figure 4.3 - Examples of field observations useful for understanding geomorphic and sediment transport processes and interpreting the field results (left) Mixing of Ayeyarwady (turbid) and low-sediment bearing Myitnge River waters, and (right) sediment deposit in the N'mai Hka showing poorly sorted deposition of river gravels and fine-grained material indicative of mudflows and very high energy environments

Recent bank samples — Riverbanks were investigated and monitored in each of the geomorphic zones. At each bank site, a transect was identified up a bank face for surveying and sampling. Attempts were made to identify transects that had deposited sand from the previous wet season preserved and as intact as possible. Due to the investigations being conducted at the end of the dry season and start of the next wet season, some modification to the sand deposits due to wind and/or humans or animals was unavoidable. A profile of the bank was recorded using leveling techniques, and sediment samples were collected at the bank toe and at ~50 cm height intervals up the bank profile. Depending on the characteristics of the site, additional samples were collected of older alluvium forming the valley wall, or the floodplain. Photos and Global Positioning System (GPS) readings of the site were also recorded. The collected samples were subsequently analysed for the distribution of grain-sizes. An example of a riverbank profile showing sediment sampling locations is shown in



- Figure 6.3.

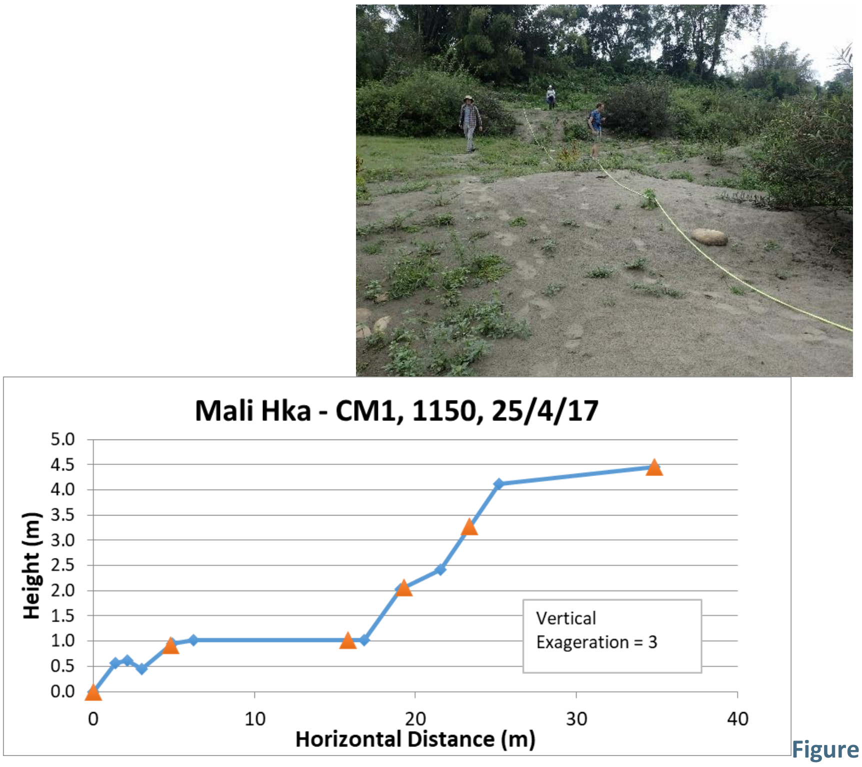


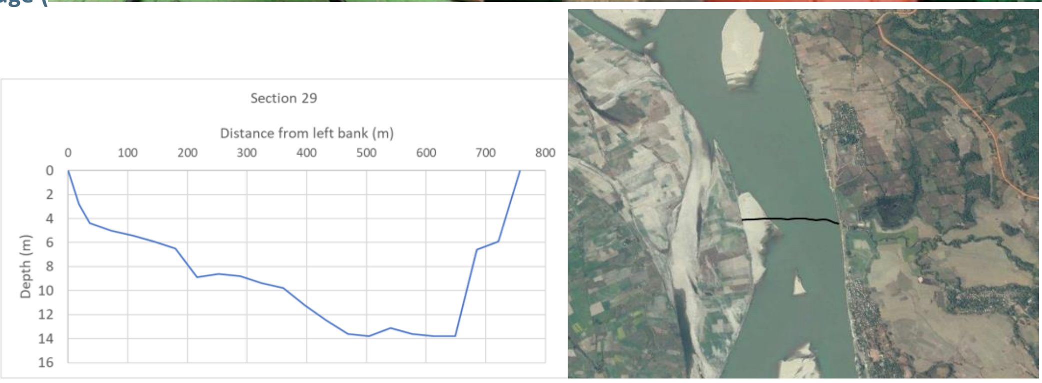
Figure 4.4 - Photo of bank monitoring and bank profile showing the locations of sediment samples.

- Historic sandbank samples — Much of the channel of the Ayeyarwady cuts through historic sediment deposits that presumably reflect older floodplains and channels. These banks were sampled to understand the potential sources of different sediments and to compare the grain-size characteristics of these historic deposits with the material presently transported by the river.

Figure 4.5 - Photos of older river deposits along banks of the Ayeyarwady.

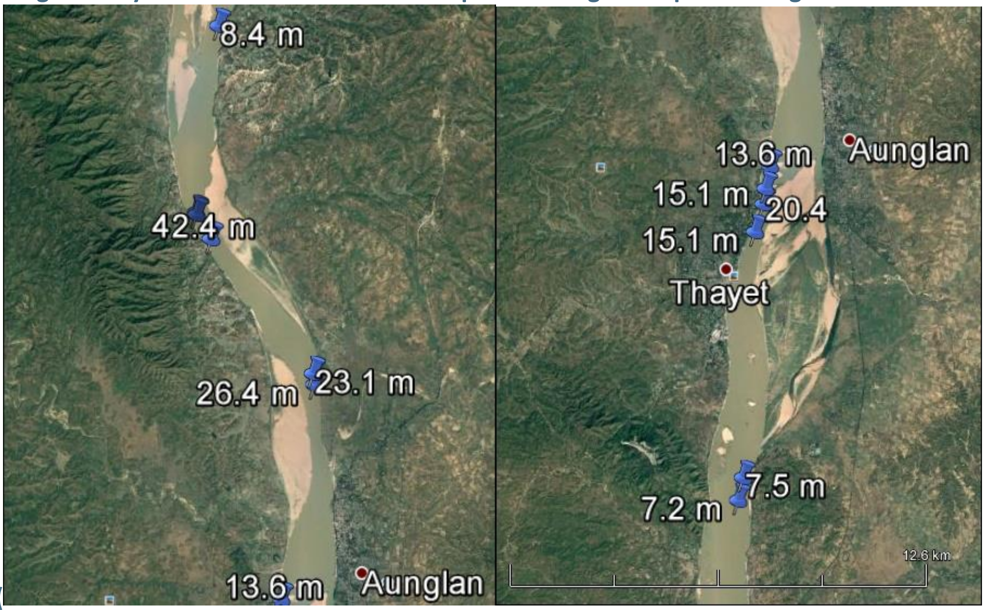
Riverbed profiling and sampling — Channel cross-sections were recorded using an echo sounder and GPS enabled camera. Photos of the echo-sounder depth and bottom topography were taken at short time intervals (5 to 10 seconds) as the boat moved across the channel. The photos provided a record of the bathymetry of the section and an indication of the bedforms present, such as the sand waves evident in

Figure 4.6. Based on the depth and profile of the bed, bed material samples were collected using a pipe dredge (



- Figure 4.6).

Spot bathymetric measurements obtained as the boat progressed downstream were also collected to understand the geometry of the river channel with respect to the geomorphic setting of the riverbanks and



valley (

- Figure 4.7).

Figure 4.6 - Photos of echo-sounder and pipe dredge sampler and example of river cross-section constructed using the photos

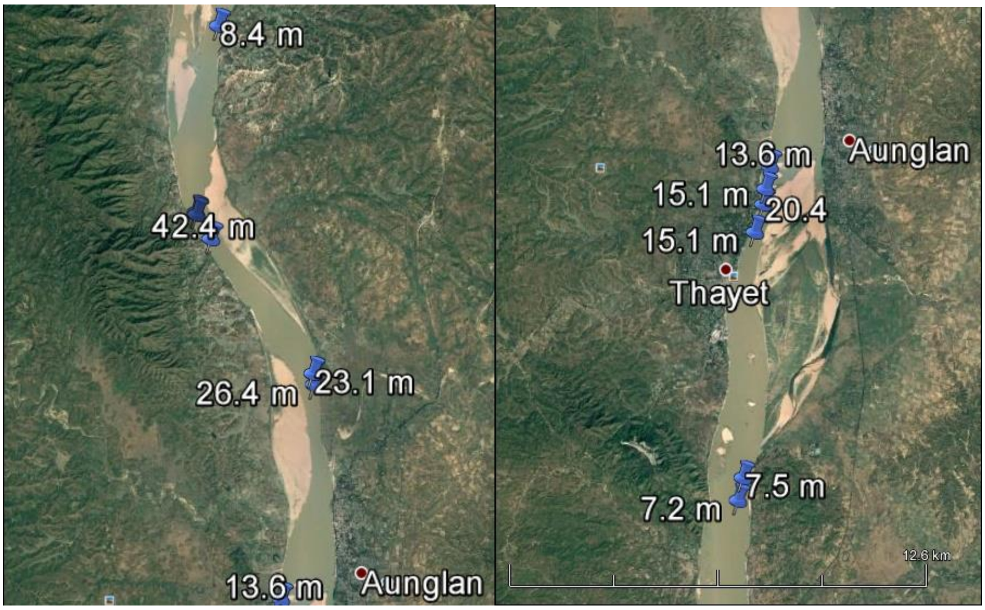


Figure 4.7 - Google earth image showing depth of river channel based on bathymetric readings while in transit on the boat

- Total suspended solids sampling — At most cross-sections, a surface water sample was collected near the middle of the channel between the depths of 5 and 30 cm. To collect the sample, a plastic bottle was lowered into the water column pointing upstream, parallel to the direction of the current. The water samples were subsequently analysed for TSS.

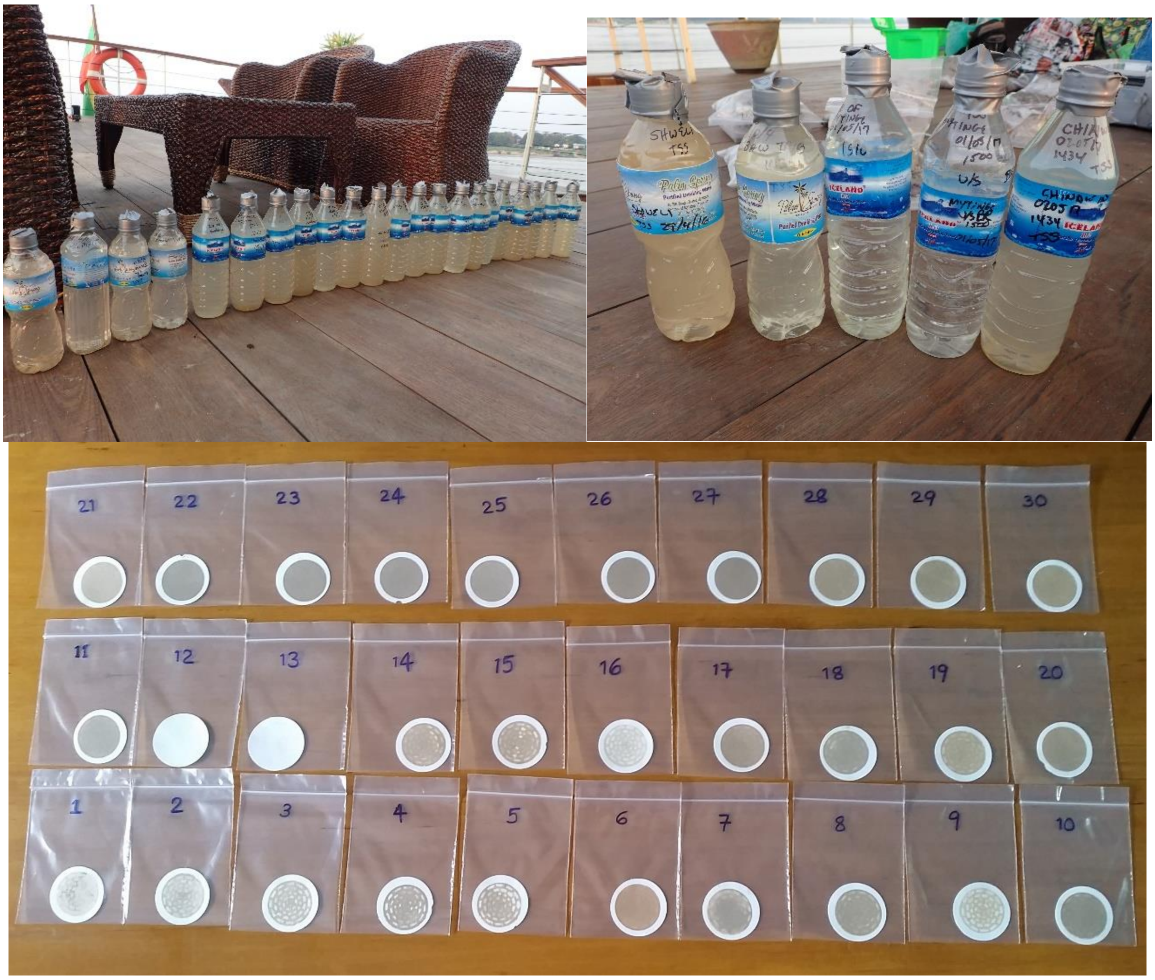


Figure 4.8 - Photos of TSS samples collected from the (left) Ayeyarwady and (right) from tributaries and (bottom) photo of TSS filters showing different colours of sediment the Ayeyarwady and tributaries

At least one of each type of sample (bank, older bank/floodplain, bed, TSS) was collected from each zone if possible. Sampling locations and the types of samples collected at each site are summarized in

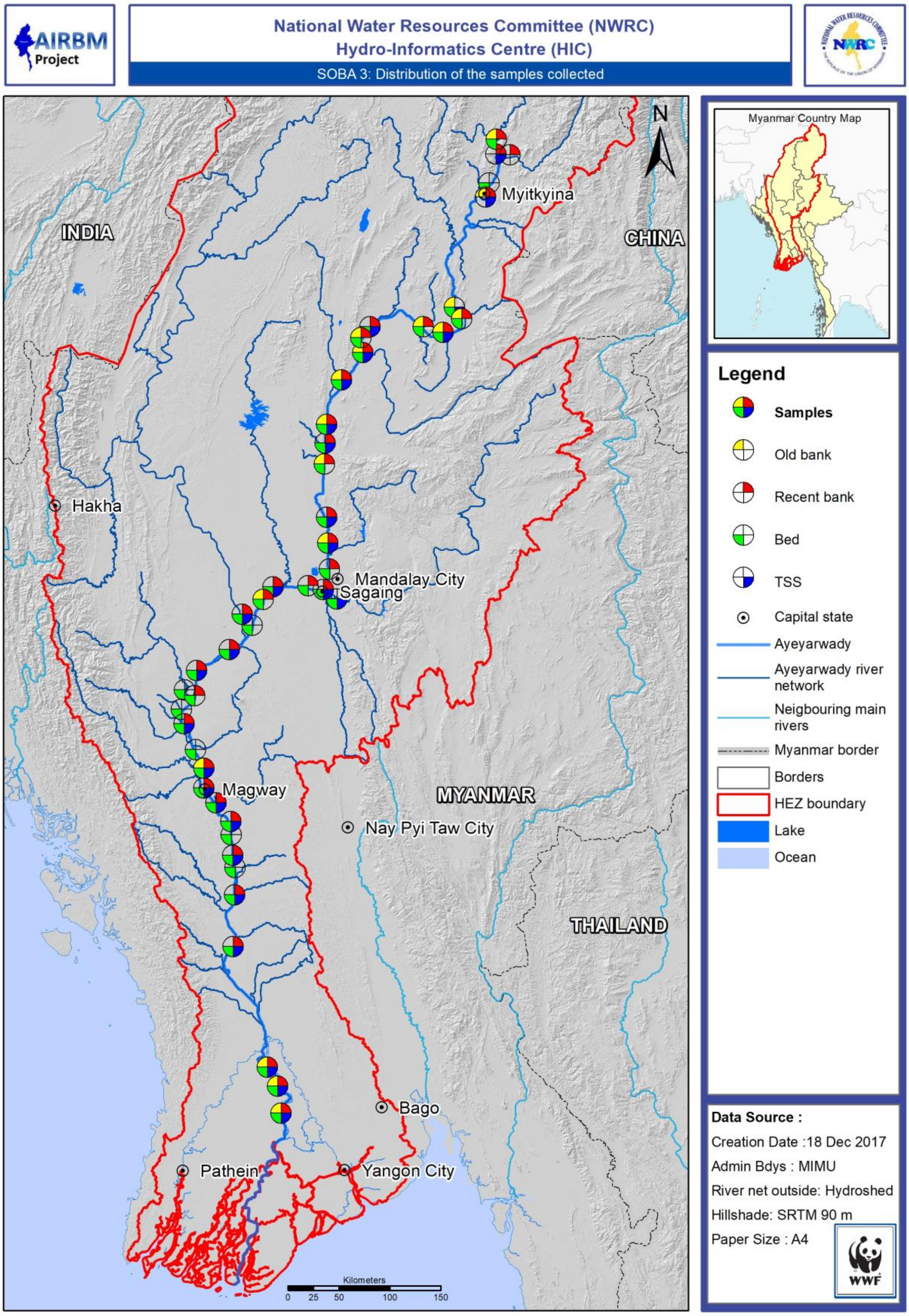


Figure 4.9. More detailed maps of each zone showing the sampling locations are contained in Annex 2 - *Geomorphic zones*.

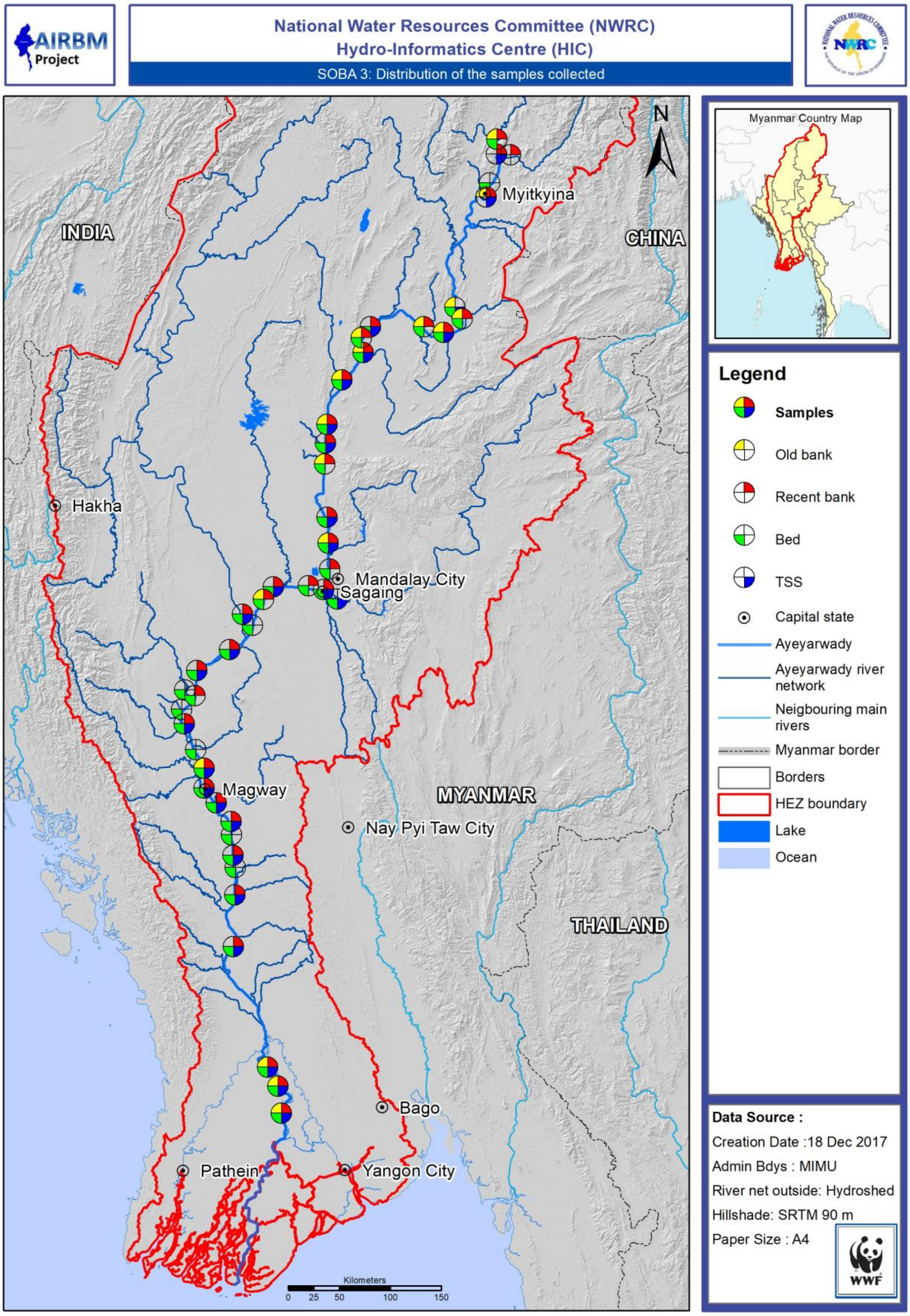


Figure 4.9 - Map showing the distribution and types of samples collected during the field investigations conducted between April 24 and May 10th

4.2.2 *River conditions during the field investigations*

The SOBA 3 Team planned on completing the initial field reconnaissance trip during the dry season, when riverbanks have their greatest exposure, and bank profiles and samples can be collected from the minimum (dry season) water level to the top of banks. Due to the final timing of the SOBA project, this was not possible and field work was completed in late April. The dates of the expedition coincided with one of the first flushes signalling the end of dry season, when water levels increased up to several metres at the established gauging stations in the river. Relative river levels (not surveyed to the same datum) show that the SOBA 3 Team progressed downstream with the peak of the high flow event.

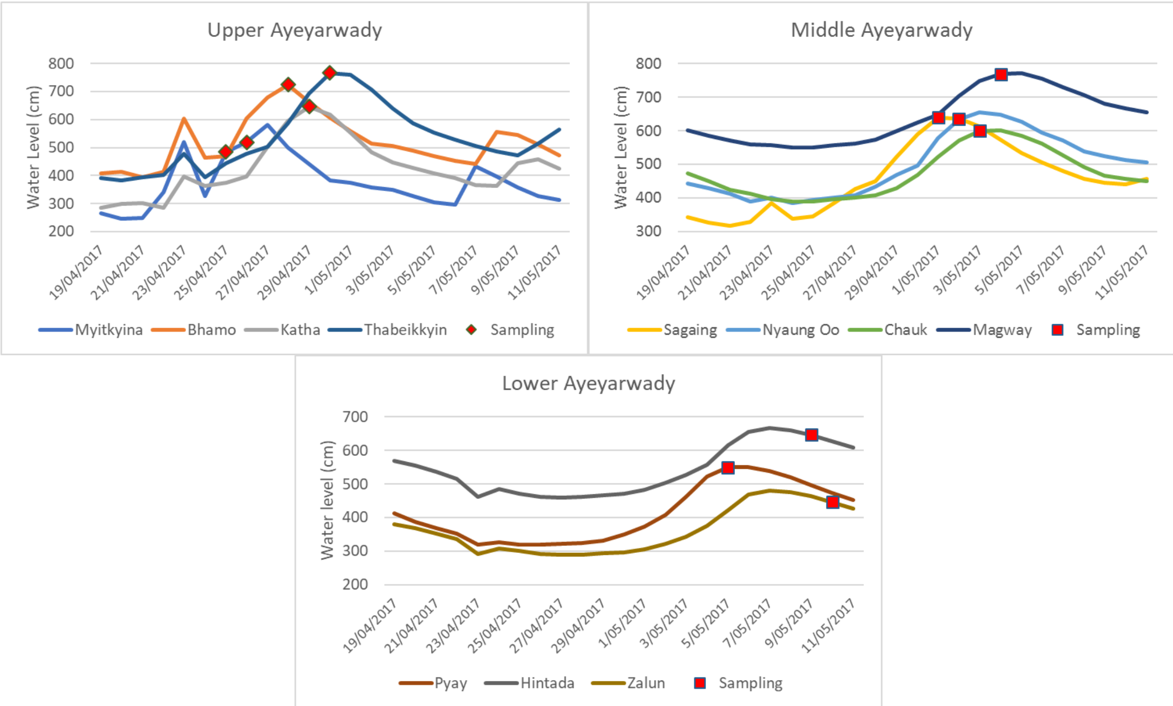


Figure 4.10 - Relative water levels for the week prior to the SOBA 3 field expeditions and during the investigations. ***Red boxes indicate the date of sampling in the different areas (Data from DMH)***

4.3 Results of Field Investigations

4.3.1 *Observations of sediment input and transport*

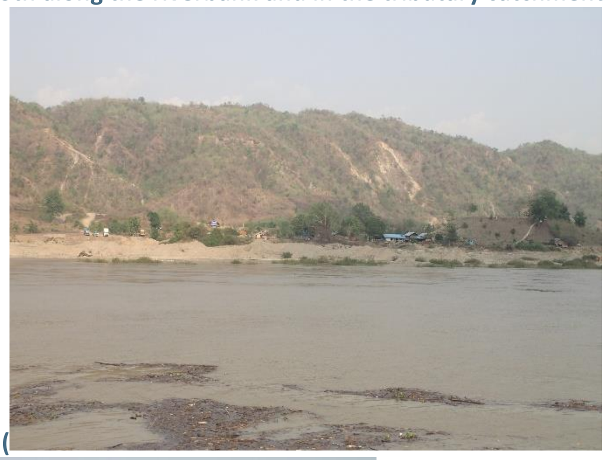
Field observations provide a context within which to interpret sample results and identify important sediment transport and geomorphic processes. Descriptions of each of the geomorphic zones are provided in Section 2.6 and Annex 2. Additional information about the monitoring sites and river cross-sections are included in Annex 5. The following discussion provides a high-level overview of some of the field observations that the SOBA 3 Team have found relevant to the discussion of sediment transport.

- The range of sediment sizes present in the banks and bed of the river was surprisingly limited. River-derived boulders and cobbles were observed on the banks in the headwaters and in zone A, but in few other locations, as fine to medium sands dominated most bank and bed deposits. This dominance of fine sand in banks throughout the river (including the headwaters) was surprising and interesting, and likely related to the relatively low slope of the river, which limits the transport of even fine sand to periods of high flow. The production of large volumes of fine sand upstream of the confluence of the N'maiN'mai and Mali Hka was also notable, suggesting aggressive weathering in the steep headwaters of the river, and/or fine-grained sedimentary deposits susceptible to weathering. The abundance of this material on the bed is consistent with it being deposited during the dry season.

- Notwithstanding the previous observation, there was a general trend of increasing coarse sand and gravel with distance downstream, with an accompanying decrease in fine material. Gravels rarely comprised more than a few percentages of the total sediment sample collected, and were present almost exclusively in bed material samples (or in locations of banks where they were deposited as bedload). These coarser materials appeared to enter in two distinct areas: as pulses associated with intense rainfall events, and as the water level rises at the onset of the wet season when bank scour rates are high. These coarse riverbanks are colluvial (e.g. derived from the weathering of the hills bordering the river) rather than alluvial (transported by river processes). The areas identified as gravel sources include:

Zones H and I, corresponding to where the Ayeyarwady Valley coincides with the Sagaing fault zone. At least two processes were identified that are likely to increase the transport of gravels. Firstly, the narrow river valley consists of steep easily erodible materials with sparse vegetation. These banks provide large sediment inputs during periods of high rainfall due to low cohesion and the steep slopes. The lack of riparian vegetation also promotes high levels of scour during the rising stage of events (

Figure 4.11). Secondly, there is a high level of land disturbance in this reach associated with mining activities. Mining disturbance occurs both along the riverbank and in the tributary catchments entering the



Ayeyarwady in this area (

Figure 4.12 and

– Figure 3.11 in Section 3.2). Land disturbance associated with mining activities can greatly increase sediment loads due to deforestation, direct ground disturbance, and through the generation of mining spoils, which are often deposited near or within river channels.

Figure 4.11 - Photos of easily erodible material along the Ayeyuarwady River in geomorphic zone 'I' shere the river occupies the Sagaing fault zone

Figure 4.12 - Land disturbance associated with mining activities along the banks of the Ayeyarwady, and tributaries delivering sediment from land disturbances in tributary catchments

– The Central Dry Belt — Many of the riverbanks in this zone also consist of easily erodible material with steep slopes. These banks become friable (easily eroded) under prolonged hot and dry conditions, and are then susceptible to attack during rainfall events. Stamp (1940) made similar observations:

> *'Climatic conditions in the dry belt are conducive to rapid erosion of the soft Irrawaddian sands and the terraces with their remarkably flat surfaces are seamed by deep, precipitous-sided watercourses, dry except immediately after rain. In this*

> *'bad land' type of topography it is a wonderful sight to see a "chaung come down," a dry watercourse perhaps 400 yards wide converted into a mass of swirling brown water in the course of a few minutes'.*

Many of the hillsides in this area are affected by mining and other land uses that increase susceptibility to erosion. These observations are consistent with the poorly sorted material deposited with the tributaries entering the Ayeyarwady in this area (


Figure 4.13).

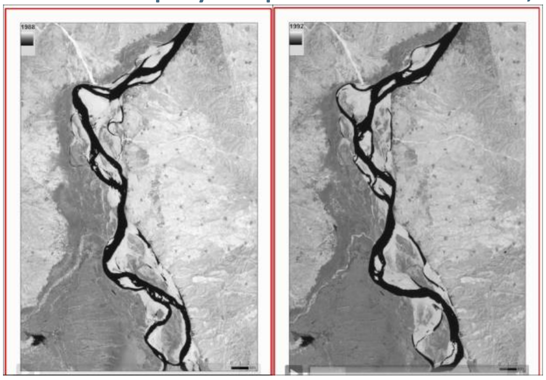
The input of sediment from these areas is likely to be episodic and vary considerably from year to year, depending on the magnitude, intensity, and frequency of rainfall events, as well as the rate of water level increase in the onset of the wet season and the duration of the wet season. Following a large sediment influx event, it may require several years for the pulse of material to work its way through the system. In the interim, there may be substantial changes to the local channel slope and bed level. Satellite imagery shows that the dry tributary channels and deltas are built up by floods when they reach the margin of the alluvial plain. The lack of reworking by the Ayeyarwady channel allows the accretion of these alluvial fans until the lateral shifting of the Ayeyarwady channel eventually erodes these deposits (

- Figure 4.14). Thus, the episodic nature of sediment input will increase the natural variability of the system. These types of sediment delivery processes need to be considered when trying to establish sediment budgets, balances, or models.

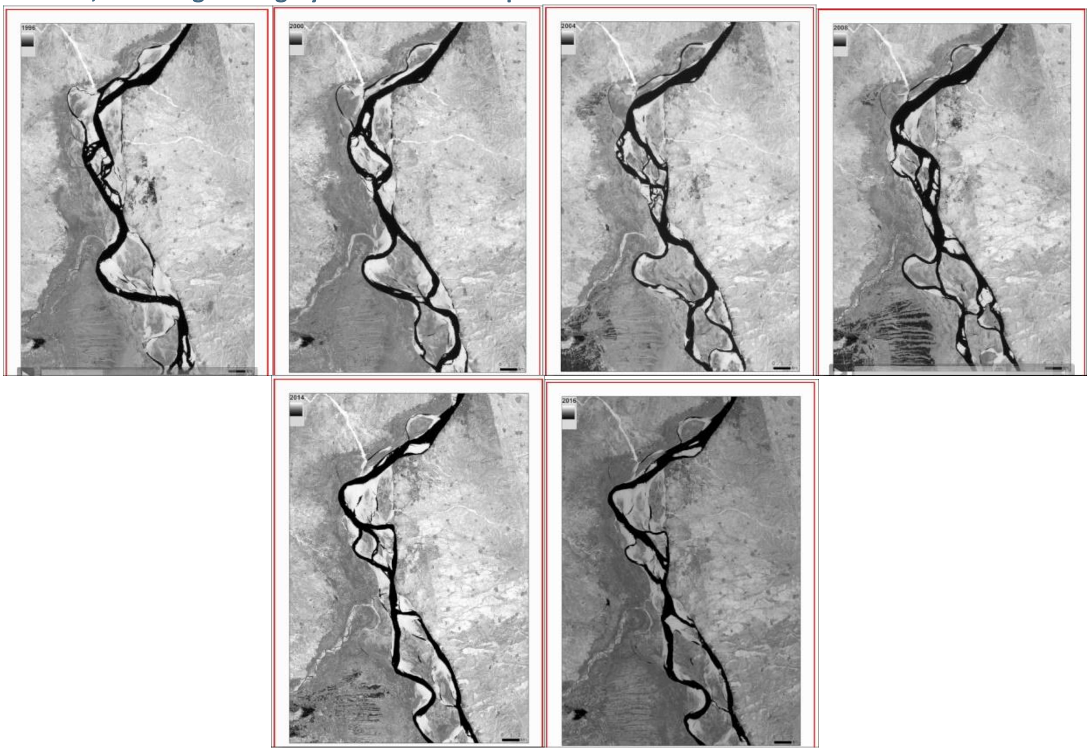
Figure 4.13 - Photos of the gravel input areas in the Central Dry Bel. (top) steep easily erodible hillsides along the Ayeyarwady (bottom) small scale mining occurring on steep slope near the river and the coarse material being transported by a small tributary

Figure 4.14. Satellite image of the Dry Zone near the town of Chalk showing the storage of sediment in alluvial fans in the tributaries. ***The large accumulation of sediment in the tributary channels is also visible. Photo from February 2017***

The areas in which the river occupies broad valleys, has multiple braided branches and is highly active appear to have high levels of biodiversity, owing to complex arrangements of sandbanks and bars and a wide range of hydraulic and hydrologic conditions present, which combine to create a mosaic of habitats. Within short reaches, there were still backwaters, and a range of channels present of variable sizes and depths. Many birds were observed in these broad, sand-rich, low-slope areas. It was evident that as water levels rose and fell, as the characteristics of these habitats would alter rapidly. Of specific note are zones B,



D, G, L and M, including the highly mobile reach depicted in



- Figure 2.24 in the channel migration discussion.

The banks and bars in the river displayed clear evidence of ongoing channel changes and activity. Most apparent was the reworking of mid-bars with erosion and deposition evident (

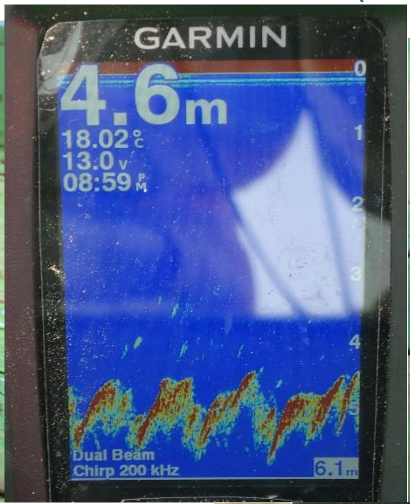
- Figure - 4.16). The wide-spread occurrence of bank reinforcement works, utilizing a range of approaches and materials, is clear evidence that the activity of the river is affecting towns and villages and has a high cost.

Figure 4.15 - Examples of different habitats present within a small area of the branching and braided river in zone B

Figure - 4.16 Photos of active mid-stream banks in the Ayeyarwady

Figure 4.17 - Photos of bank protection measures along the Ayeyarwady mainstem.

The bedforms observed in the echo sounder reflections (



- Figure 4.18) taken at each cross-section provided the following information about sediment transport processes:
  - Sand dunes were common at depths up to ~8 to 10 m in most cross-sections. The amplitude of the dunes ranged from ~0.5 to 1.5 m and the width of the dunes was estimated at up to ~10 m. These features are indicative of moderate flow rates.
  - Steeply sloping channel margins were smooth, indicative of higher shear stresses with depth.
  - The bed of the deepest sections of the river (>10 m during the sampling trip) also showed few sand dunes or other features, consistent with higher shear stresses resulting in a planer morphology.

Figure 4.18 - Bed forms as recorded from river cross-sections. Top row of photos shows features associated with depths up to ~8 m, bottom row shows features commonly observed in deeper areas of the channel.

The Sagaing fault zone provided historic insights beyond sediment transport. The SOBA 3 Team discovered a tooth and partial jawbone on the eastern bank of the fault zone approximately 6 km south of Male and 10.5 km north of Thabeikkyin, near the village of Gway Pin Hmaw (

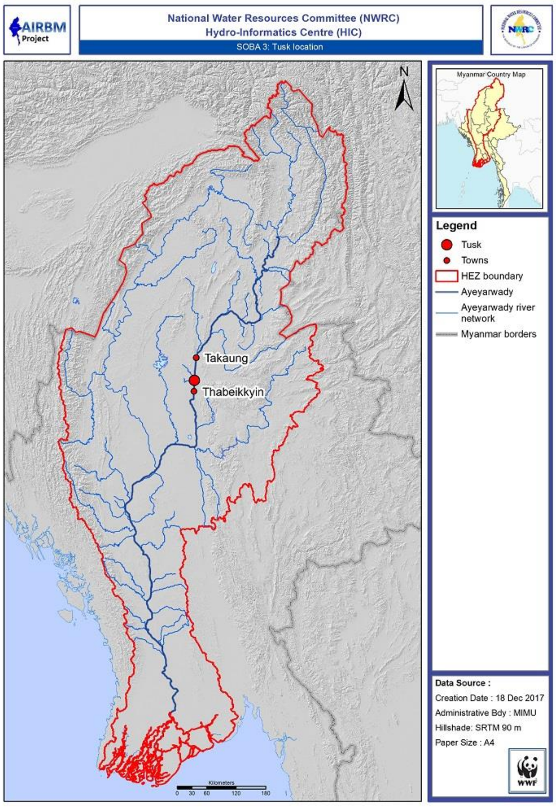
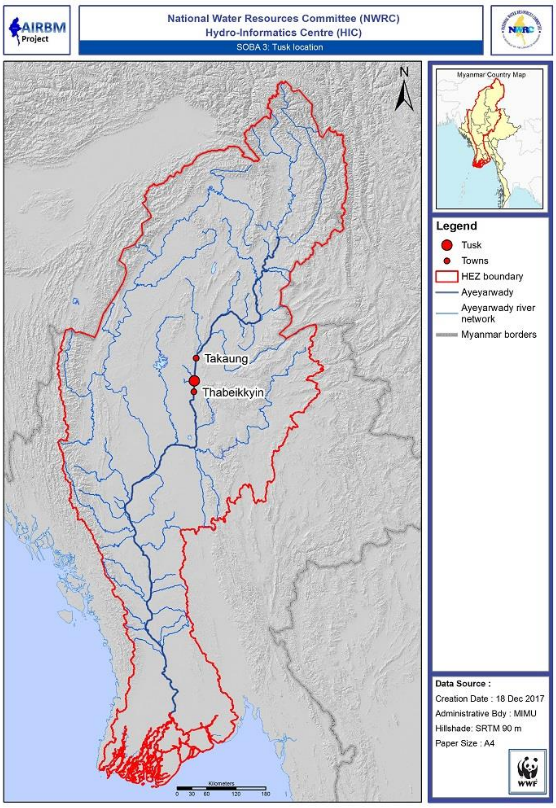


Figure 4.19). The strata are identified as Miocene on geologic maps and based on consultation with elephant experts the fossils are likely from a Stegodon, an extinct member of the elephant family recognised as being the largest member of the proboscideans and known to have inhabited the area. The fossils were collected and transported to Yangon where they were transferred to the Project Management Unit (PMU). Photos of the tooth in situ and being extracted are shown in



- Figure 4.19, along with a location map and model of a Stegodon.

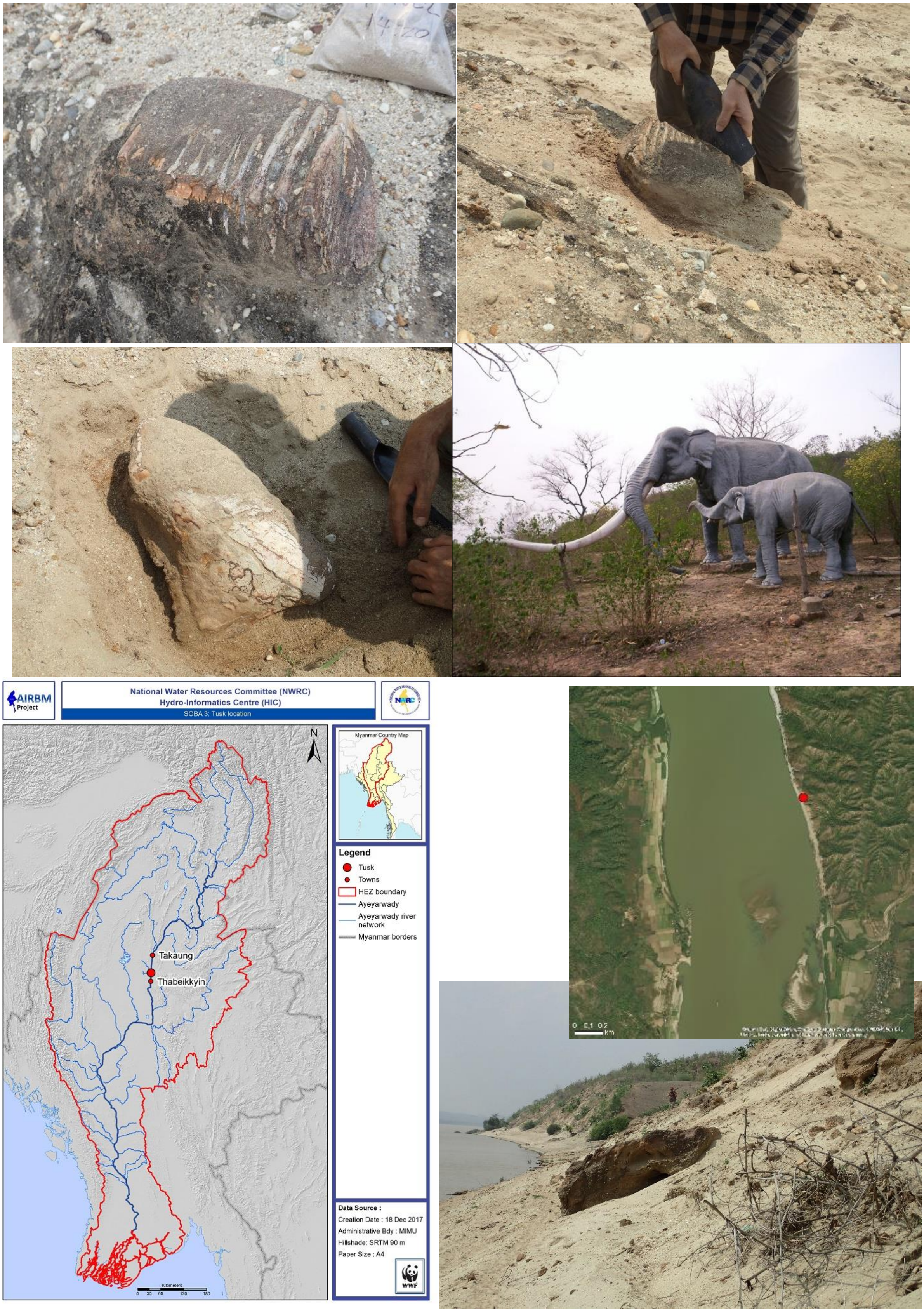


Figure 4.19 - (top) Miocene Stegodon tooth in the Sagaing fault zone (middle) jaw bone and model of extinct species (model from Wikipedia); (bottom) location and setting of fossils.

4.3.2 Sediment characteristics

A total of 362 sediment samples were collected during the SOBA 3 field investigations, with 236 collected from the active banks of the river, 89 from the riverbed and 37 from older floodplain and bank deposits.

The grain-size distribution of each sample type is shown in

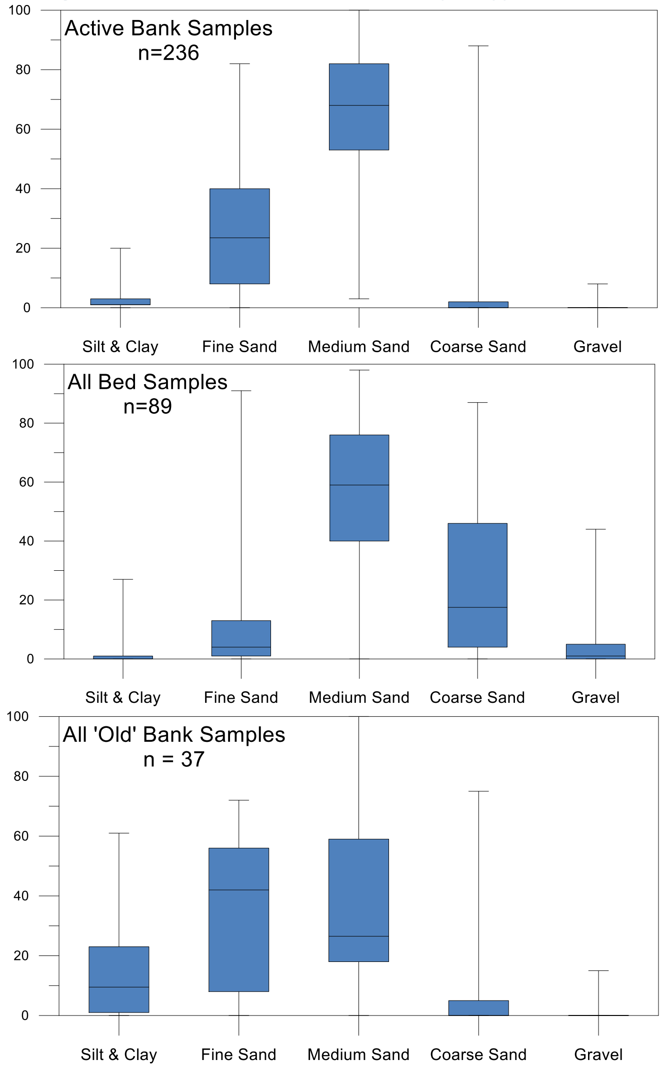


Figure 4.20. The results include all samples of each type from all zones in the river. There are similarities and differences between the sample types, reflecting the modes of deposition. The recent bank samples are dominated by fine and medium sand, with very low percentages of silt and clay, or the coarser sediment components (coarse sand and gravels). These materials have been deposited under a fixed range of flow conditions with shear stress sufficient to continue to transport silts and clays (thus accounting for their absence) but not strong enough to carry coarser material, thus limiting deposition.

The historic old banks and floodplain deposits show similarities, as the majority of the material is composed of fine and medium sands, suggesting similar depositional settings as the active bank samples. However, there is a higher percentage of fine sand and silts and clays in the sample set as compared to the active banks. This reflects the inclusion of historic floodplain deposits, that were deposited outside of the main river channel under conditions of lower shear as compared to the active banks in the present Ayeyarwady channel. The finer grain-sizes may also reflect the in situ weathering of sediments, as evidenced by their rich red colour, indicative of iron oxidation associated with weathering processes. The colouration and weathering are consistent with most of these deposits being mapped as Holocene on geologic maps (see Annex 1).

The bed materials contain a majority of medium-grained sand, suggesting similarities in depositional conditions as the active banks. However, the bed materials contain a higher percentage of coarse sand and gravel. These larger material sizes are transported by the river at depth as bedload (rolling or bouncing along the bottom) or in suspension due to the higher shear stresses deeper in the water column as compared to the banks. Fine sand was present on the surface of the bed at several sites even through the flow velocity and depth suggested that the bed could be transporting much coarser material. These samples are interpreted as being deposited during the previous dry season (as sampling was conducted at the end of the dry season), with the high-flow flush that occurred during the sampling campaign insufficient to remove all of the fine material accumulated since the previous high flow season.

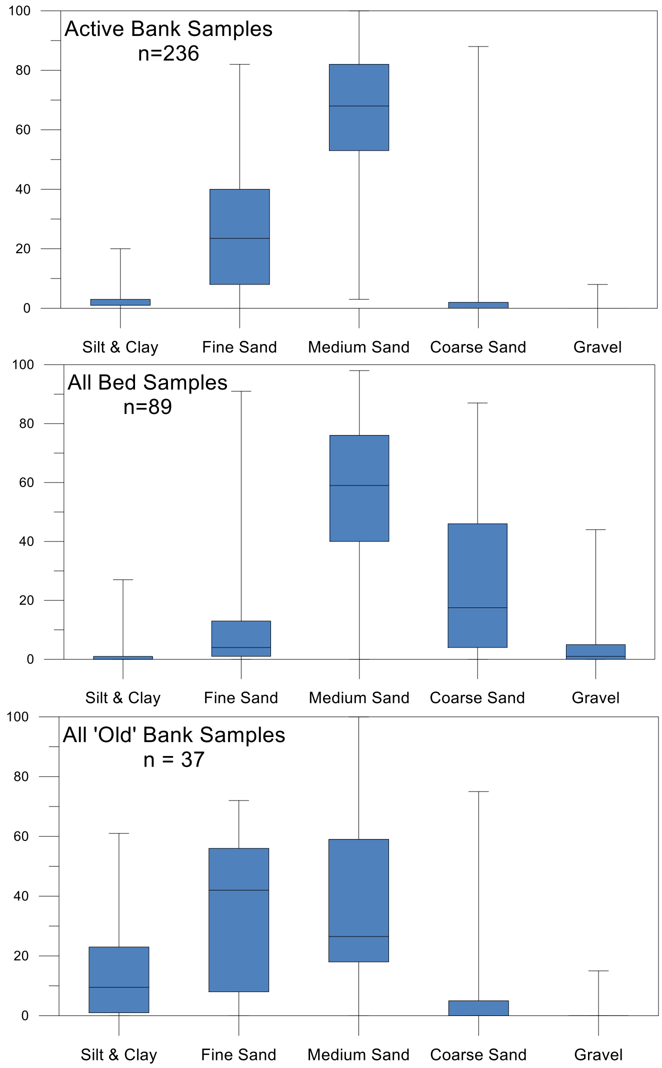
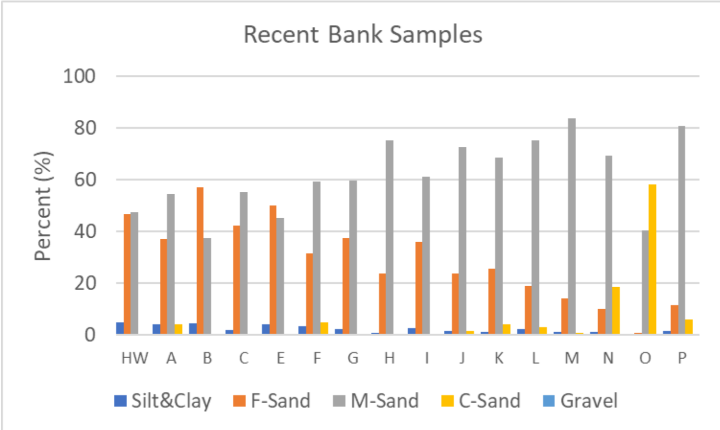


Figure 4.20 - Box and whisker plots of the grain-size distribution of bank, bed and older bank / floodplain deposits collected during the SOBA 3 field expedition (top) Active (recent) bank samples (middle) river bed samples (bottom) old bank and floodplain samples. *The box encompasses the 25th to 75th percentile values, with the median indicated by the horizontal line. The minimum and maximum values of the data set are shown by the vertical 'whiskers'*.

The sediment grain-size results from each type of sample show trends when interpreted by zone. The active



bank samples (

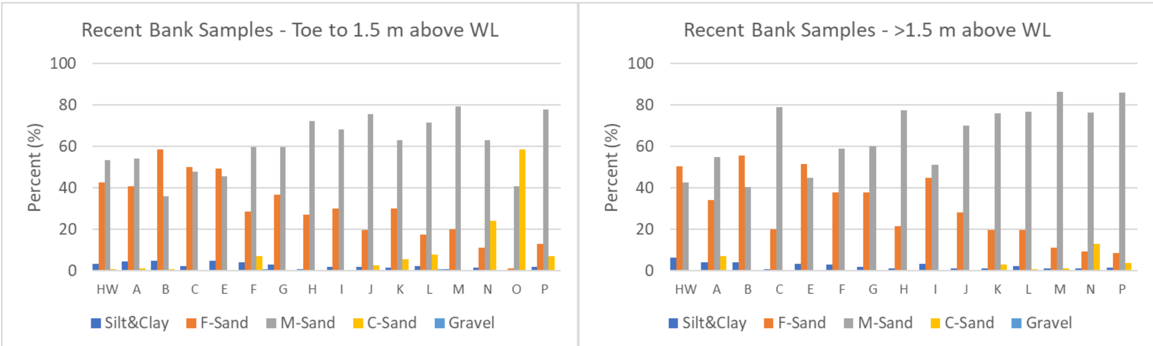


Figure 4.21) show a distinct decrease in fine sand and increase in coarse sand and gravel with distance downstream. Zone O shows the highest proportion of coarse sand, but only one bank was able to be profiled in this zone, so the results are limited. When the results are grouped by bank location as well as zone, as in the bottom graphs, the coarser material is associated with the bank toe and lower bank face. This is consistent with the coarser material being transported as bedload or in the lower part of the water column as suspended material during high flows. There is a reduction in the fine sand component in the upper bank face that may reflect some winnowing of fine material by the wind during the dry season as well.

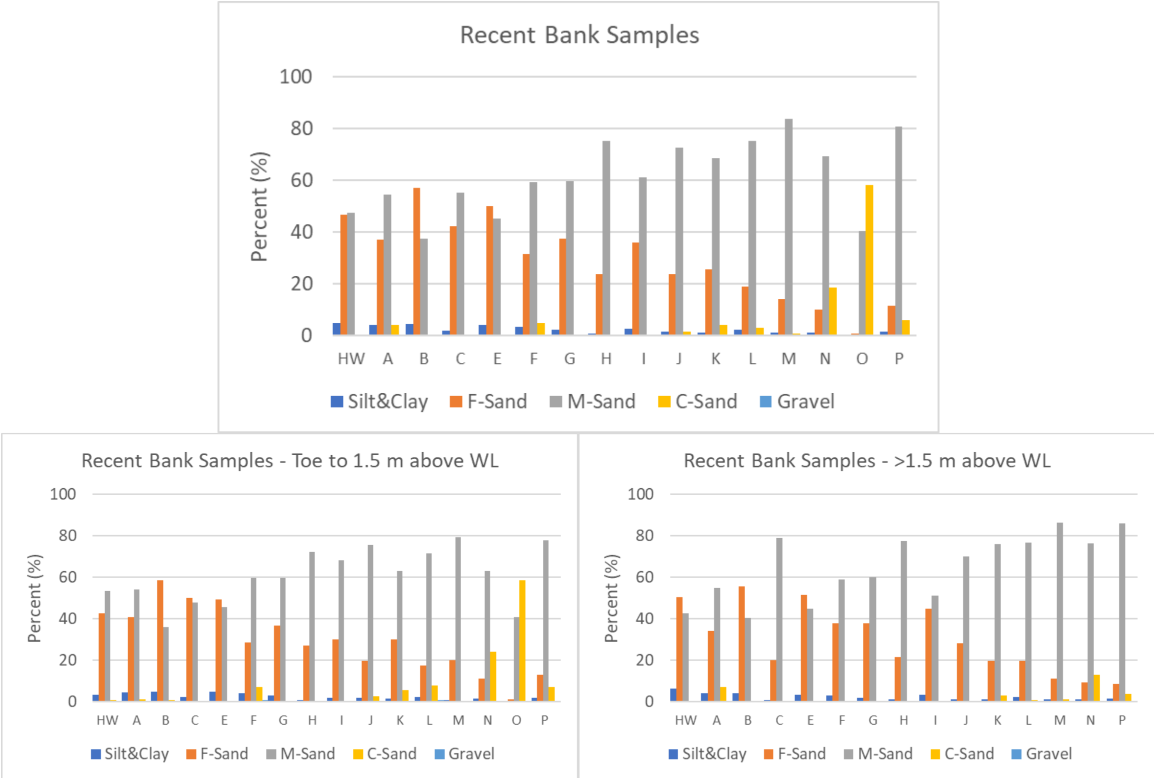


Figure 4.21 - (top) Sediment grain-size results for samples collected from active banks by zone and (bottom) divided into bank toe and lower bank face (water level to ~1.5 m) and upper bank face (>~1.5 m): *x-axis denotes geomorphic zones*

The bed sample results show more variability as compared to the bank samples (

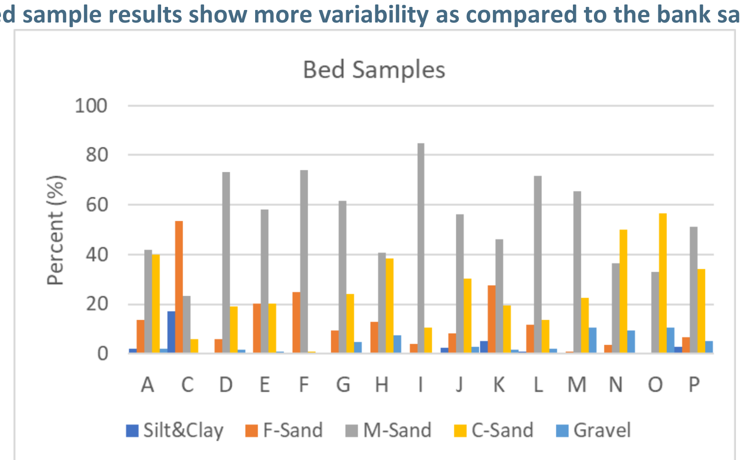


Figure 4.22). There is a decrease in fine sand with distance downstream, accompanied by an increase in coarser material. As previously noted, the abundance of fine sand in the upstream sites at the beginning of the field work is interpreted as reflecting material deposited since the previous dry season. An increase in coarse sand occurs downstream of zone L, which is where the river flows through the steep, easily erodible hills in the Central Dry Zone.

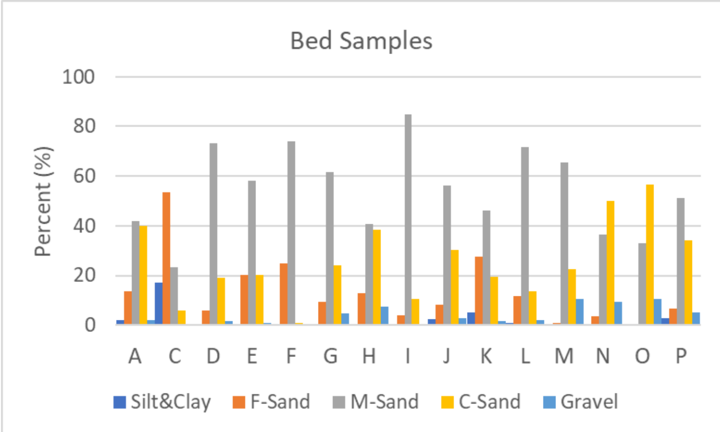
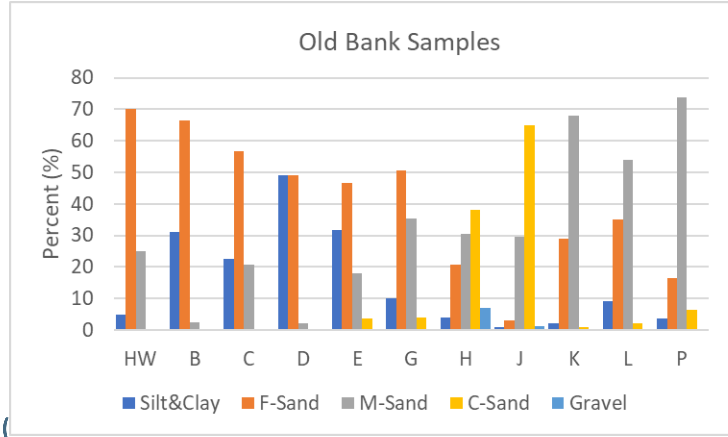


Figure 4.22 - Bed sample grain-size results grouped by zones. ***x-axis denotes geomorphic zones***



The old bank and floodplains samples (

Figure 4.23) show similar trends as the recent bank samples with fine sand decreasing, and medium and coarse sand increasing down the course of the river. The presence of coarse material in zones H and J likely reflects the input of coarse material from the Sagaing fault zone. The higher silt and clay content in zones B, D, and E is consistent with these zones being characterised by low slopes and broad valleys, and providing depositional areas downstream of more confined bedrock controlled reaches.

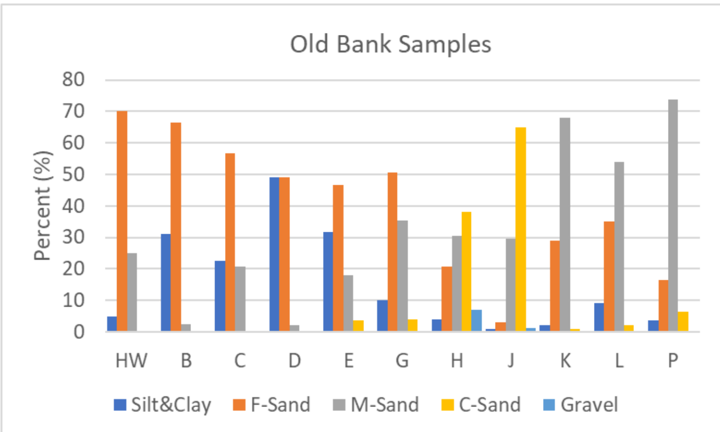


Figure 4.23 - Grain-size distribution by geomorphic zones of historic bank and floodplain samples. ***x-axis denotes geomorphic zones***

4.4 Total Suspended Solids

4.4.1 TSS concentrations and distribution

The surface water samples collected for Total Suspended Solids (TSS) were analysed by a laboratory in Yangon by filtering each through a pre-weighed glass fiber filter with a nominal 0.5 µm pore size, and then re-weighing. The results are shown in

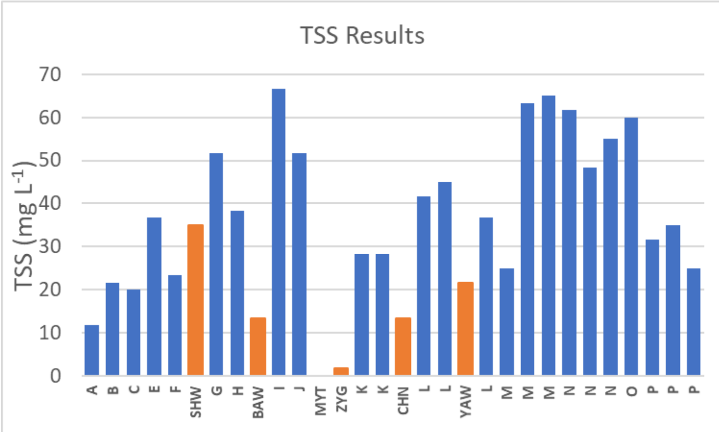
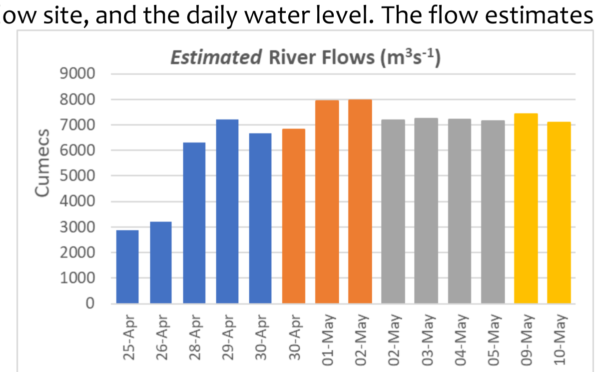


Figure 4.24, with the main stem of the Ayeyarwady shown in blue and the tributaries in orange. In the Ayeyarwady, the TSS results ranged from 11.7 milligram per liter (mg L^{-1}) to 66.7 mg L^{-1} with an average of 40.5 mg L^{-1}. In the tributaries, TSS ranged from Not Detectable in the Myitnge River to 35 mg L^{-1} in the Shweli River. There was a general increasing trend in concentrations from zones A to J, reduced concentrations in zones J, K, L, and the start of M, and then higher concentrations in the remainder of zone M through zone O. The samples in zone P were collected several days after those in zone O, and thus cannot be interpreted as a continuum.

The TSS concentrations are low, but similarly low surface sediment concentrations were recorded by Gordon in 1877 to 1878, with values of <40 mg L^{-1} presented on graphs in the Robinson et al., (2007) re-analysis of the data. Robinson et al., (2007) also noted that the ratio of surface concentrations to mid-depth concentrations in Gordon's dataset was ~0.8, and the concentration of suspended sediment in bottom depth samples was two to four-fold higher than the surface concentrations. This demonstrates that the total sediment transport occurring in the river is far greater than indicated by the surface samples alone.

4.4.2 Sediment transport based on TSS results

Estimates of flow were made for four sites in the Ayeyarwady, based on the recently reviewed rating equations (Walker, 2017) and the published water level at the respective site from the DMH website. The four sites provide good coverage of the Ayeyarwady: Katha provided an estimate for flow in the upper Ayeyarwady, Sagaing was used for the middle Ayeyarwady upstream of the Chindwin, Nyaung Oo was used to estimate flows downstream of the Chindwin, and Zalun was used for the delta. Flow was derived for each sampling day using the rating equation at the closest flow site, and the daily water level. The flow estimates derived are shown in



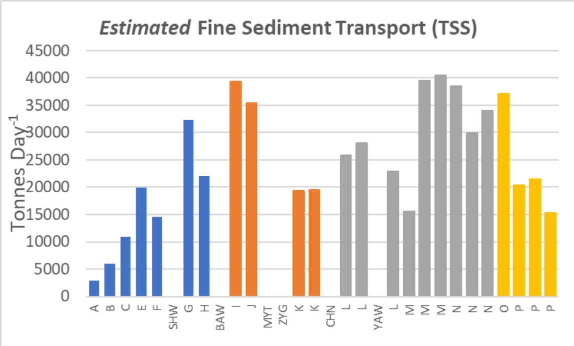
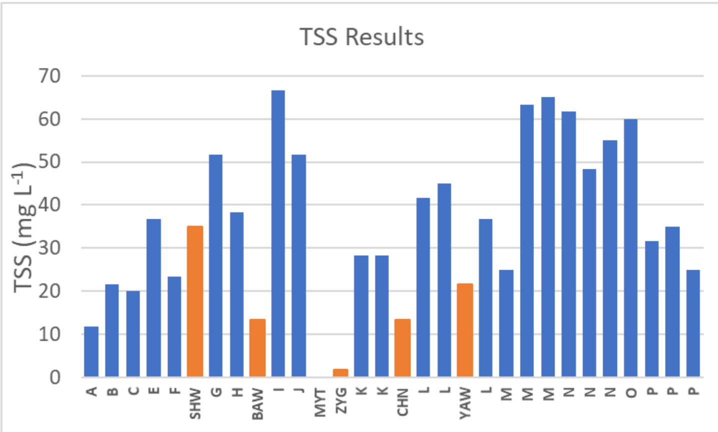


Figure 4.25 (left). The flows ranged from <5,000 m^3s^{-1} at the start of the trip in Katha, to ~8,000 m^3s^{-1} at Sagaing. Flow generally increased over time and with distance downstream between Katha and Sagaing during 25 April to 2 May. The calculated flow decreased between Sagaing and Nyaung Oo even though the Chindwin enters between these sites. This suggests there is a potential error at one or more of the sites that is consistent with the findings of the Activity 1 Review (Walker, 2017), which highlighted the difficulties of determining an accurate flow at Nyaung Oo due to the highly mobile nature of the riverbed.

Using these flows and the TSS results, *estimates* of sediment fluxes were derived for each of the TSS monitoring sites. These values are considered very rough estimates and should be considered as only indicative. TSS only captures surface water, and the collection bottle used does not capture a flow proportionate accurate sample, but rather collects results that are likely to be underestimates compared to the total sediment load transported by the river on a given day. No sediment flux estimates are presented for the tributaries, as there are no flow estimates available for these rivers.



The sediment fluxes (Figure 4.24) range from <5,000 t day^{-1} at the most upstream sites to ~40,000 t day^{-1} in zones M and N. The sediment fluxes show increases through the upper Ayeyarwady through zone J, followed by a decrease in zones K and L before increasing again in zone M and downstream. The TSS loads determined for the delta (zone P) are lower than upstream, but were collected several days later and reflect the lower TSS recorded at these downstream sites.

Stamp (1940) summarized Gordon's 1887 to 1878 suspended sediment data on a monthly basis, and found that February and March had similar average daily sediment fluxes (39,000 and 42,000 t day^{-1}) to those estimated for April/May 2017 using the TSS results. However, the historic results were based on considerably lower average monthly flows (2320 to 2375 m^3s^{-1}) and much higher suspended sediment concentrations (195 to 205 mg L^{-1}) compared to the recent results. In the historic dataset, the monthly sediment load recorded for the periods of low sediment flux (February and March) only contributed ~1% of the annual sediment load.

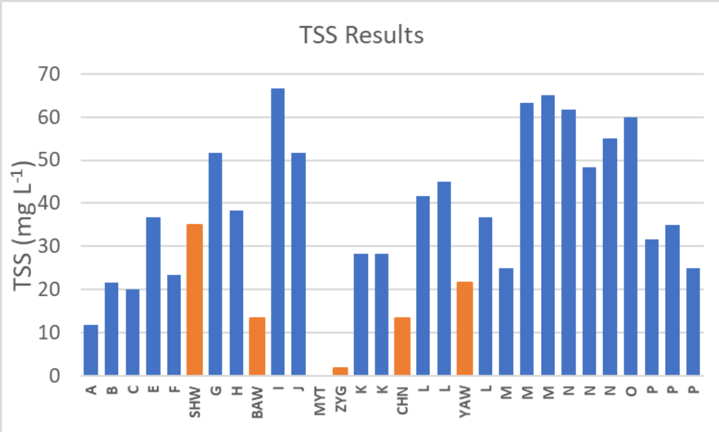


Figure 4.24 - Total Suspended Solid (TSS) results (mg L^{-1}) collected between April 25 and May 10, 2017.

Blue bars show results from mainstem Ayeyarwady, orange bars show results from tributaries. Letters 'A' through 'P' indicate geomorphic zone. Tributaries: SHW = Shweli, BAW = Baw, MYT = Myitnge, ZYG = Zawgyi, CHN = Chindwin, and YAW=Yaw (x-axis denotes geomorphic zones and sample points)

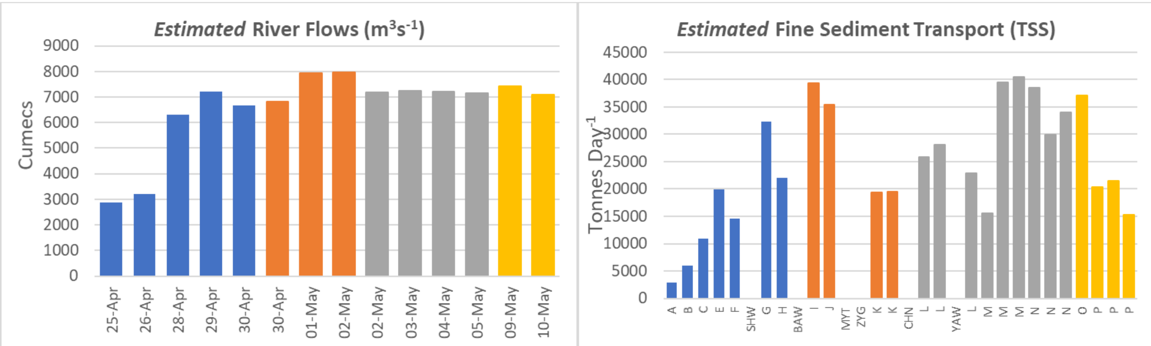


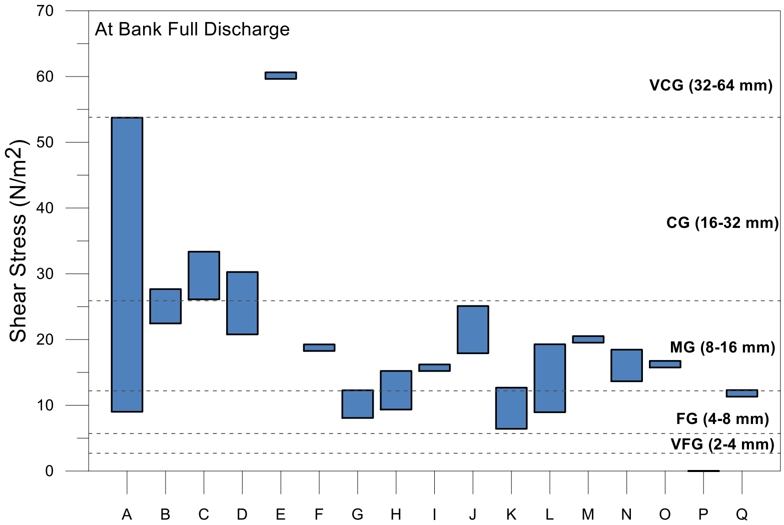
Figure 4.25. (left) Estimated river flows on days of TSS sample collection.

Blue bars based on water level and rating curve for Katha, Orange bars based on Sagaing, Grey bars based on NyaungOo and Yellow bars based on Zalun (right) Estimated sediment loads based on TSS and discharge results. Colour of bar indicates which flow station was used to calculate results. X-axis shows sample locations by geomorphic zone. No transport estimates made for tributaries as no flow estimates are available. (x-axis denotes geomorphic zones and sample points)

4.5 River Energy and Sediment Transport

Sediment transport is determined by the shear stress in a river. When the shear stress of the moving water exceeds the gravitational force holding sediment in place, sediment transport will occur. Shear stress in turn is governed by the slope of the river and the depth of the water. Shear stress was estimated for each zone of the Ayeyarwady to provide an indication of the types of materials that are likely to be transported during periods of high flow. The slope of the river was estimated based on an analysis of satellite imagery, and an evaluation of the bank-full depth of the river for each zone.

The bank-full depth for each zone was estimated by determining the difference in water level between the day the channel cross-sections were measured and the 'Danger Level' listed on the DMH website. This height was added to the average and maximum depth value of the river cross-sections collected in the zone, to provide an approximate range of high flow river depths for the zone. The river cross-sections are shown in Annex 5, and the range of shear stress calculations associated with these estimated bank-full river levels are



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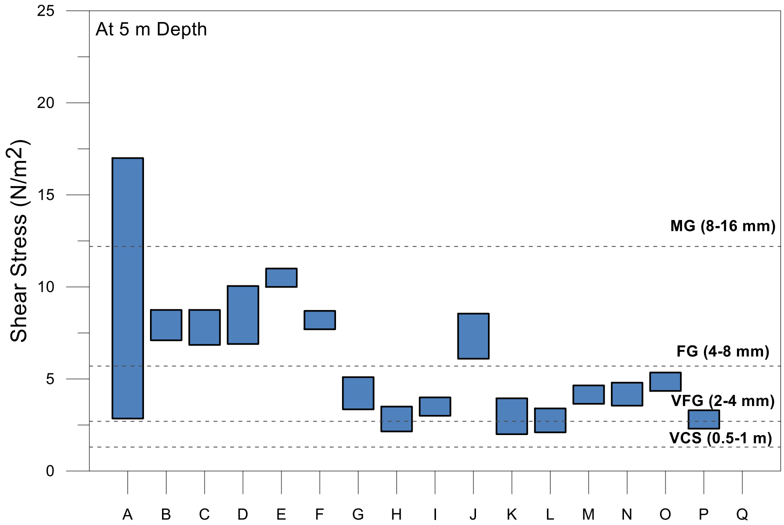


Figure 4.26 (top). The bars show the range of shear stresses associated with the different slopes occurring within the zone and the average and maximum channel depths, corrected to bank-full. Similar calculations were determined for a uniform depth of 5 m in the water column (

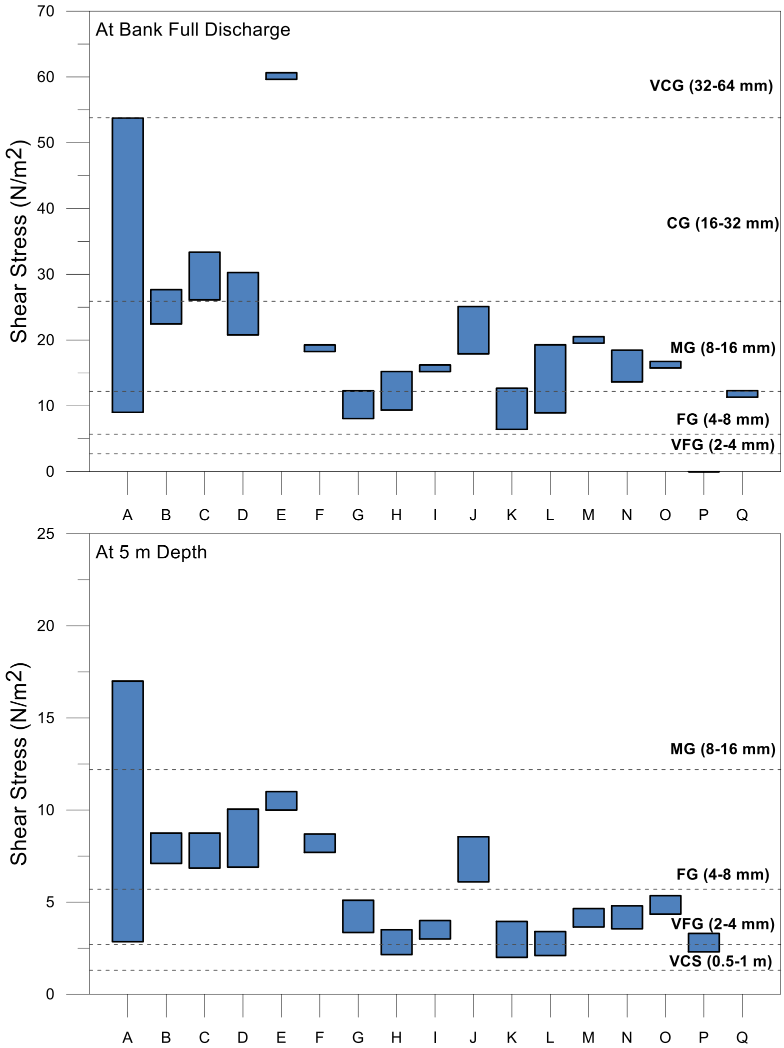


Figure 4.26, bottom) to understand how sediment is transported at water levels below bank-full.

Both sets of analysis show similar patterns, with the highest shear stresses associated with zones A through E, and low values in zones L and K. Under conditions of bank-full discharge, sediment transport in zone A could include all size fractions through very coarse gravel. This sediment range decreases to coarse gravel in zones B through D. The lower shear stresses in zones G, H, K, and L relative to the zones upstream suggest these could be areas of sediment accumulation and reworking, which is consistent with the field observations.

The calculations based on water depths of 5 m suggest that only zone A would have the capacity to transport medium gravel, and zones B through E would be limited to fine gravel. Zone J retains relatively high shear stresses even at this lower flow level, while zones K and L have much lower ranges of shear stress. This again highlights the potential for sediment to be readily transported through J but then get stored in zones K and L until higher flow velocities are available. Of course, once these higher flow velocities occur, coarser material is transported through J and delivered to K and L, so these areas of the river will inevitably be areas of sediment deposition.

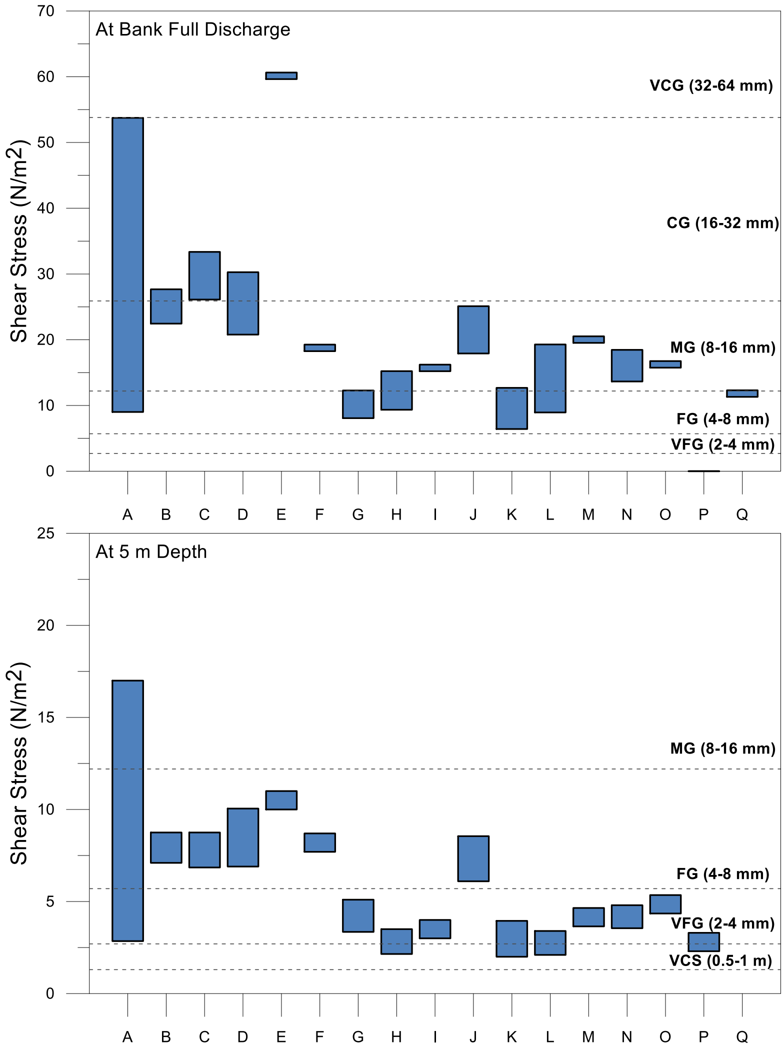


Figure 4.26 - Range of shear stress calculated for (top) 'bank full' discharge based on average and maximum channel depths at time of investigation in April / May 2017 adjusted to the 'Danger' WL listed on the DMH website and (bottom) range of shear stress at a water depth of 5 m. *Dashed lines indicate approximate limits of transport for different grain sizes with size range indicated in mm: VCS = very coarse sand, VFG = very fine gravel, FG = Fine gravel, MG = medium gravel; CG = coarse gravel, VCG = very coarse gravel. Note difference in scale between the two graphs*

4.6 Sediment Transport Based on Grain-size Distribution

The grain-size distribution of the samples collected along vertical transects on the active sediment banks in the Ayeyarwady were used to infer the mode of transport prior to deposition using the CM method (Passega, 1957), which provides insights into sediment transport processes and river functioning. A CM graph provides an image composed of a collection of points, each representing one sample. There is a consistent image or model for all rivers in the world, but each river and each particular reach inside a river displays its own unique signature. River processes are deduced from the position of individual CM points in the graph, and depositional environments can be characterized by the pattern produced by all samples.

For these reasons, the CM images are presented at a zone scale, and include all of the samples from each site sampled in the zone. The sites were selected for their ability to represent characteristic fluvial landforms and processes operating in the active channel in each zone.

The CM method uses the ratio between the coarsest grain-size 'C' where C = the 99th percentile grain-size in the sample (e.g. C = D99) and 'M' the median (M = 50th percentile or D50) in the sample to deduce the hydraulics of the water column at the time of deposition. The methodology is based on how the distribution of sediment varies with depth in a river under different flow conditions. A uniform suspension occurs when river energy is sufficiently high to distribute all suspended sediments evenly through the water column, regardless of grain-size. A graded suspension occurs when river energy is sufficient to uniformly suspend fine material (wash load) throughout the water column, but larger grain-sizes are limited to suspension in the lower water column or as bedload. Sediments deposited under different flow conditions show varying ratios of C to M. These patterns can be interpreted when C and M are plotted on CM diagrams (

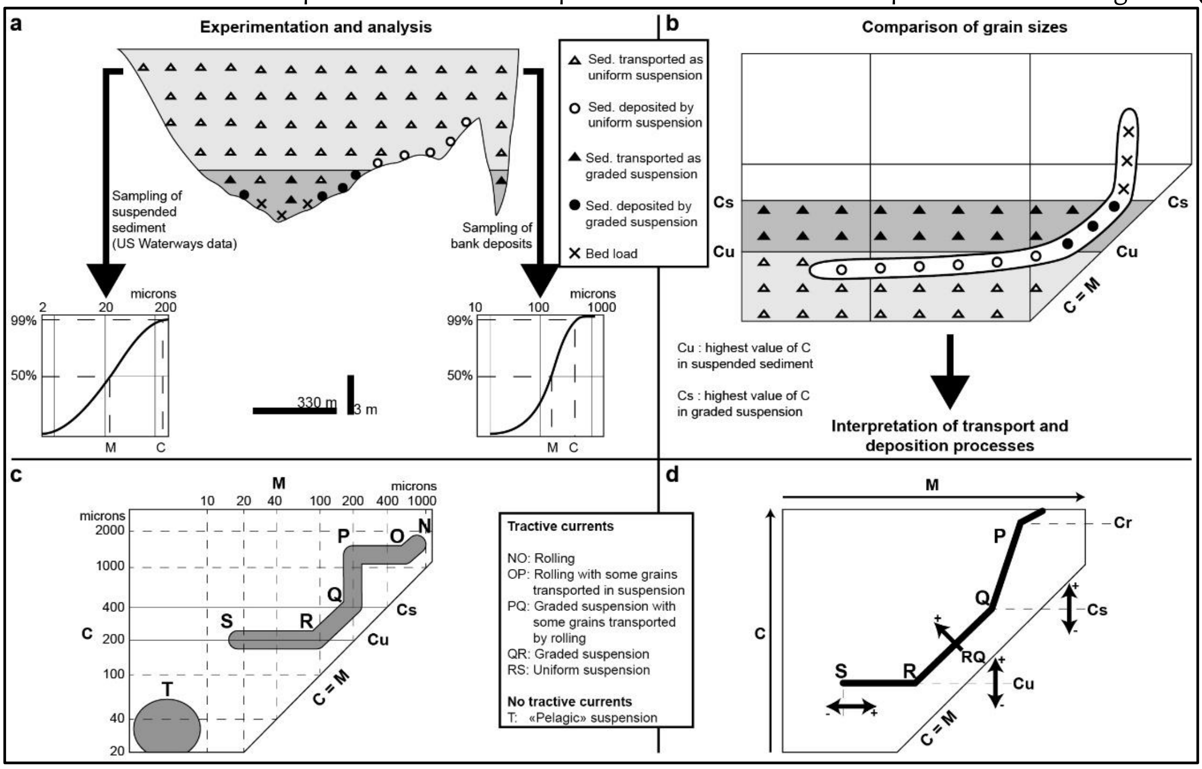


Figure 4.27) and have the following characteristics:

- During high flow, the turbulence of the river is sufficient to carry the coarsest material along with the finer sediment fraction. When the turbulence decreases during the recession of the flood, the coarsest particles settle on the banks or on the bed first, resulting in the coarsest (C) and median (M) grain-size of the deposit being similar, so that the results plot parallel to the C = M line in the area indicated as 'NO'.
- Particles that are transported by rolling along the bed (bedload), while finer material is carried in suspension plot within the segment OP on the CM graph.
- Sand transported in suspension during a flood fine upwards through the water column, resulting in graded suspension. On the CM diagram, two types are distinguished:
  - Segment PQ corresponds to a mix of rolled (bedload) particles and graded suspension. These deposits are typically present on the lowest areas of the banks.
  - Segment QR corresponds to pure graded suspension in the absence of bedload transport. Due to the graded nature of the suspended sand material deposited under these hydraulic conditions, deposits are usually composed of medium sized sand on the lower banks and fine sand on the upper banks.
- Results which plot within the RS sector of the CM diagram are characterized by a constant C value, which reflects the uniform nature of the coarsest material in the wash load being transported in uniform suspension. Variable M values reflect different bottom velocities, with the lowest values corresponding to the lowest water velocities. During the recession of a flood, as water velocity decreases, the CM characteristics of the deposited material move from R to S on the graph, due to the decreased size of material which can be deposited, but no change in the maximum size of the material carried in suspension.

- The last type of deposition is termed 'settling' (T), which occurs in still water bodies existing over a floodplain, or in dead arms, or quiescent areas of water bodies. These deposits do not exist in the channel except in small shallow swales, for instance upstream of sand dunes.
- Sediment is considered well sorted when a sample plotting along the QR segment falls close to the C = M line; it is poorly sorted when grains are dispersed, and some fall further from the C = M line.

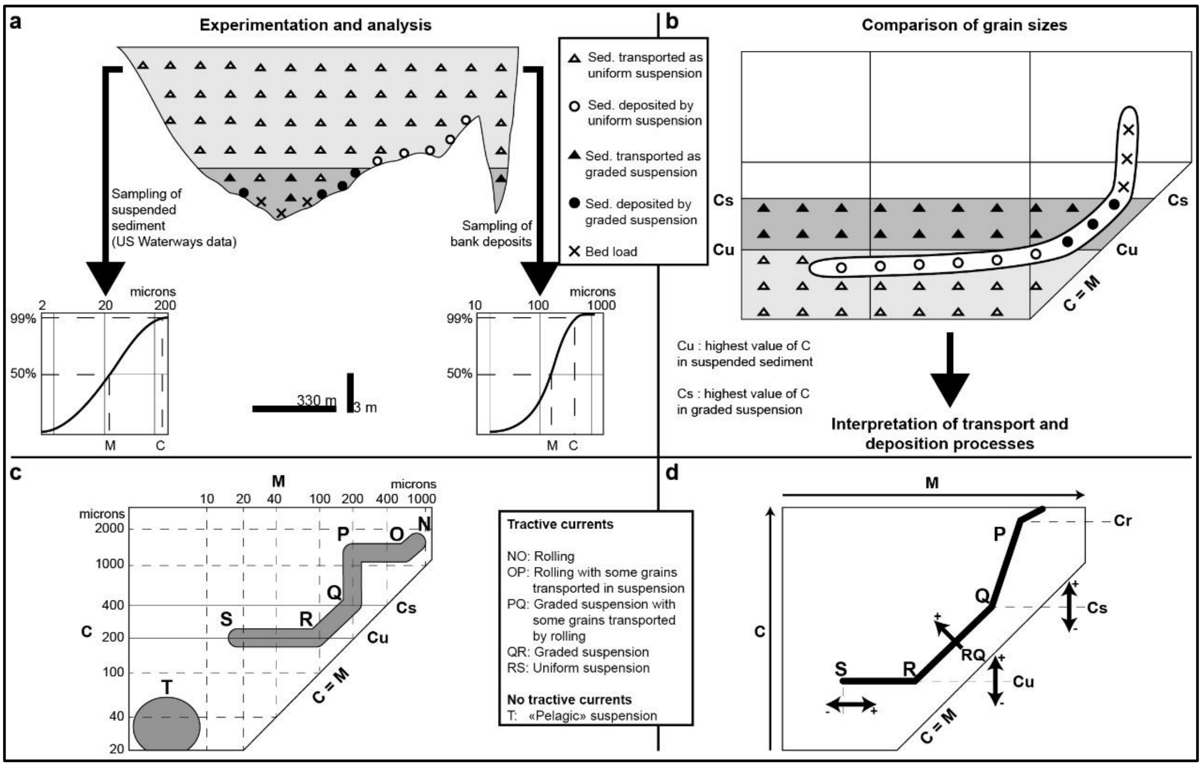
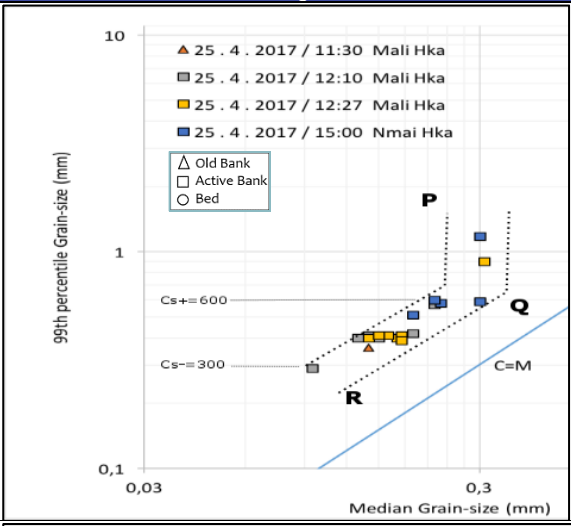


Figure 4.27 - Explanation of CM diagrams *(Based on Passeaga, 1977)*

4.6.1 Summary of CM results

One of the main challenges was to select representative locations at the site and zone scales. Locations were chosen in the active channel of the river (freshly deposited sand bars, fresh sand deposits on islands and in the channel bed). Older material was sampled from cross-sections exposed by the lateral erosion of the river to compare fresh and older sediment, referred to as eroded or 'old' banks in the discussion. A total of four types of sites were required. This typology was maintained along the river continuum, from the headwaters to the lower course of the Ayeyarwady including some tributaries. A complete understanding of the river functioning would require a wider effort, including for instance sampling inside ancient islands and former arms partly or totally disconnected from the present active tract.

For each zone, a CM diagram was constructed, with details of each site contributing to the results presented in Annex 5, along with a more complete CM report. The following points summarize the findings of the CM investigation. In each of the following graphs, the triangles indicate older bank deposits, the squares show recent/active bank deposits and the circles depict riverbed samples.

<table>
<tr><th>CM Diagram</th><th>Interpretation of CM Results</th></tr>
<tr><td>
</td><td>Headwaters: Cross-sections exposed by the lateral erosion of bars along the N'mai Hka alternate sorted sand and gravel.

Two coarse bank samples from the Mali Hka and N'mai Hka deposits are in segment PQ and may be considered as mixtures of graded suspension and particles rolled from the channel bottom (R). The topography of the bed and bars allowed the rolling of coarse sand during the flood.
Most of the samples are made of sand and belong to segment QR, originating from well-sorted graded suspension (the three sets of samples located in segment QR).
The samples from the different bars have different C values indicating different maximum turbulence.
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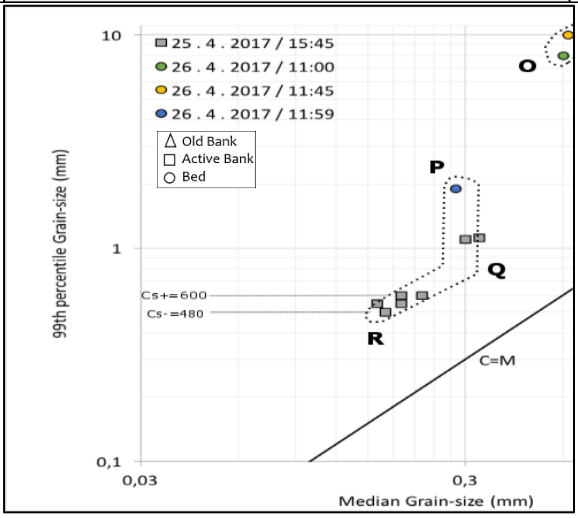
<tr><td>
</td><td>Zone A: This zone displays low lateral bars of gravels (10 to 15 cm in diameter at least); some are ancient (reddish) and others are recent. Present data include 3 bed samples and a transect across the top of a sandbar.

The bed material is small gravel transported as rolled particles (segment ON), with one sample showing graded suspension (PQ).
The lateral sandbar is protected by bushy vegetation and displays well-sorted and homogeneous sediment from graded suspension (QR segment), with some uniform suspension with maximum grain-size values of between 600 and 480 µm (lower part of PQ segment)
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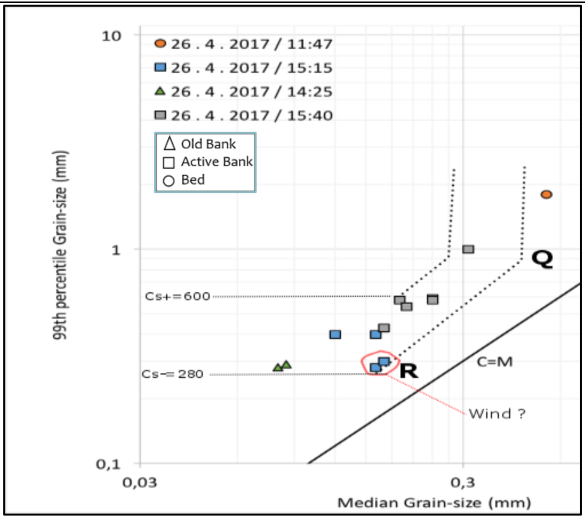
<tr><td>
</td><td>Zone B: Old and new banks and the channel were sampled in this zone.

The mid-stream sandbars sampled reflect deposition from a graded suspension with little bedload (rolling) contribution (QR segment).
The coarsest sandbar is located in a wide channel and reflects a high energy environment, with one sample in the PQ segment with C values between 600 and 400 µm (0.4 mm).
One active bank sample plots along QR with a cluster near R. This fine material may be derived from a uniform suspension of fines under conditions of low flow, or material introduced by wind.
2 samples from an eroded bank display a poor sorting and may be a mixture of fine-graded suspension and finer sand (a layer with low velocity or trapping by vegetation).
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<tr><th>CM Diagram</th><th>Interpretation of CM Results</th></tr>
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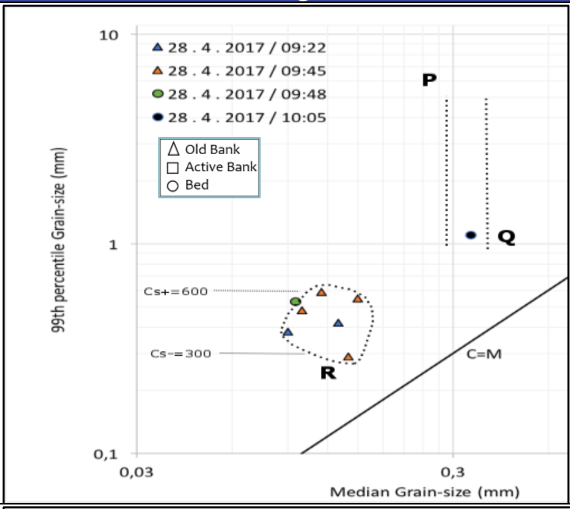

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Zone C: Two samples were collected from the bed, while the other ones were collected in eroded banks downstream of a gorge, in a widening reach.

Amongst the bed samples, one is composed of coarse sand, probably deposited after the flood peak over the coarser material; the other one, composed of poorly sorted sand, originates from graded suspension. It was enriched in finer material during the flood recession.
The eroded banks display horizontal layers of pink sandy sediment. It is made mostly of poorly sorted graded suspension, possibly due to trapping of finer particles by vegetation. Values of C are comprised between 600 and 300 microns.

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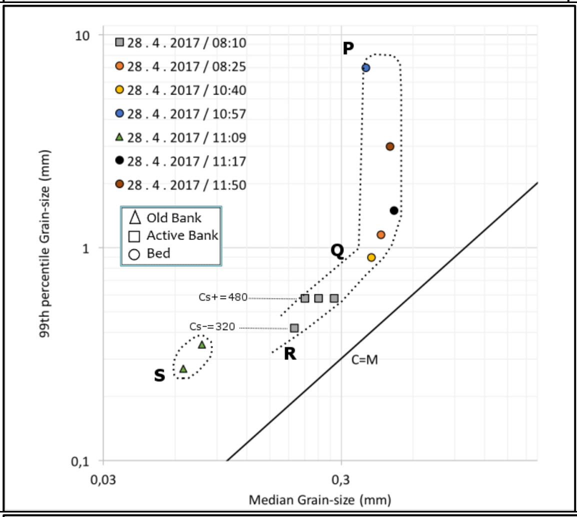

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Zone D: This zone displays well-sorted sediment fitting very well with the classical CM image processes.

The samples from the bed point distinctively in segment PQ and range from sand with some fine gravel to coarser and well-sorted gravel. They are probably deposited over a coarser lag of gravel.
A sandbar is composed of well-sorted sediment from graded suspension, with values of C comprised between 480 and 320 microns.
An eroded bank is composed of stained poorly sorted sand (fine-graded suspension enriched in finer sand inducing a low value of M). It may derive from uniform suspension due the trapping effect of vegetation.

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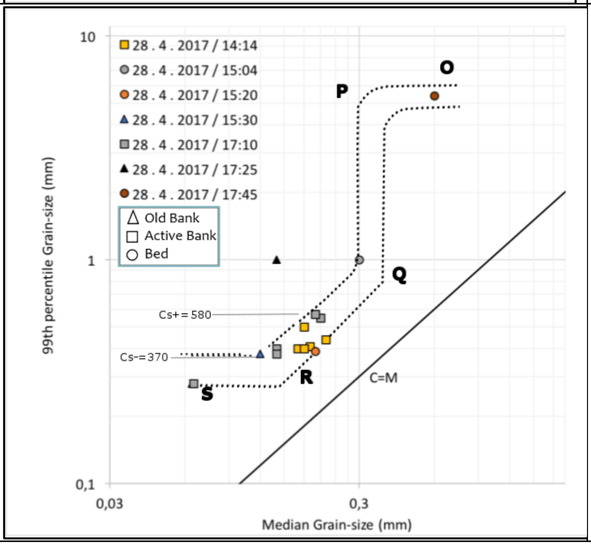

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Zone E: This zone has well-sorted sediment fitting with CM processes as in zone D.

Two bed samples are composed: one of fine gravel, the other one of coarse sand (PQ segment). A third bed sample is composed from graded suspension. All of them were deposited on the channel bottom after the last flood.
The sandbars display a homogeneous sand deposited by graded suspension (QR segment). C values are comprised between 470 and 280 microns.
Two samples were in eroded banks and a mixture of sand and finer particles: one from graded suspension, the other one from graded suspension and rolling. The low value at 280 microns may indicate a uniform suspension.

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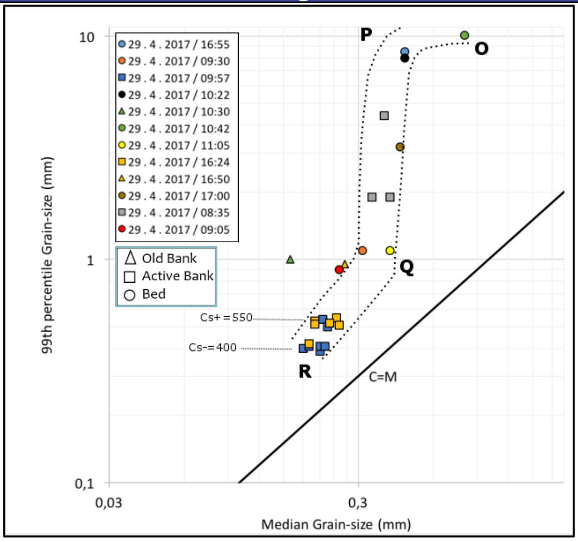

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Zones F and G: These zones display a wide range of transport characteristics.

- Bed samples show a mixture of graded suspension and rolled particles probably transported as bedload along the inclined bank. The coarsest one belongs to segment OP (rolling), while five fall in segment PQ (graded suspension and rolling).
- Two lateral sandbars were built up by pure well-sorted graded suspension. C values are uniform over the height of the section, suggesting that the velocity remained high during the flood recession.
- The last two samples from eroded banks display the same C values as samples belonging to the PQ segment, but they have a lower value of the median M because the deposits trapped the finer suspended load.

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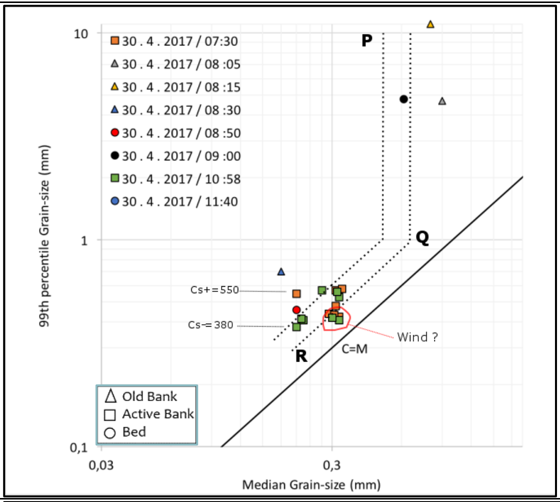

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Zone H: A range of samples were collected.

- Two bed samples correspond respectively to OP and PQ segments. The sediment is similar to coarse sediment from eroded banks.
- Another bed sample originated from graded suspension deposited after the flood, probably over coarser particles.
- Two sandbars are well-sorted sand deposited from graded suspension (QR segment).
- Two or three active bank samples fall very close to the CM line of perfect sorting, which may suggest they are influenced by wind sorting.
- Similar to the previous zone, an eroded bank sample is poorly sorted, and enriched with finer particles, probably reflecting trapping.

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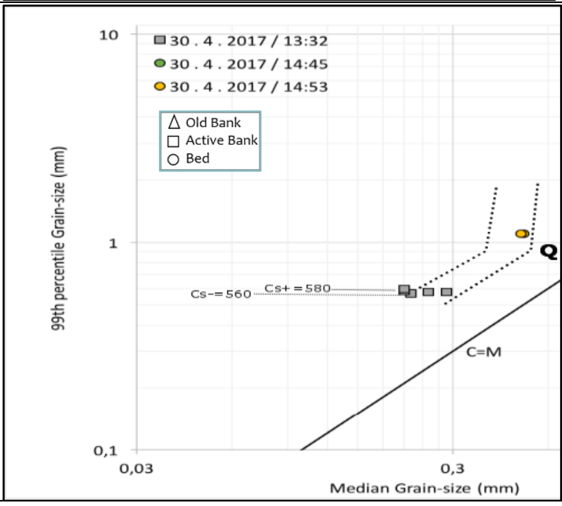

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Zone I: The active banks sample was collected from a large bar bordered by a vegetated swale.

- The sandbar originates from graded suspension (QR segment), with quite high C values of 560 to 580 µm suggesting high turbulence.
- The bed samples belong to the lower values of segment PQ with a C value close to 1 mm, indicating a combination of rolling and graded suspension.

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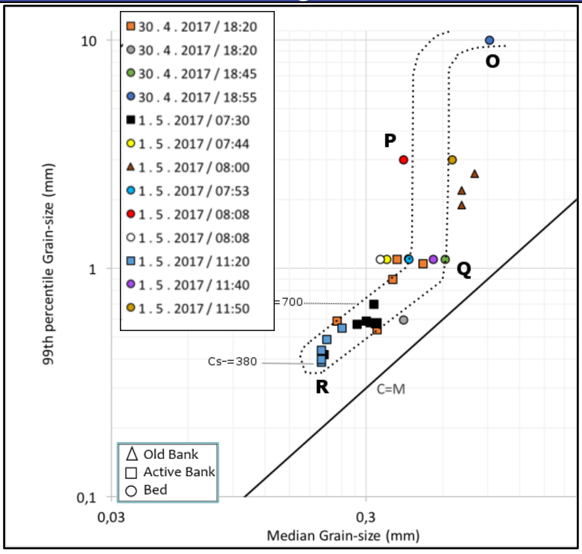

</td><td>
Zone J: This reach displays ancient lateral bars with well-sorted small gravel and crisscrossed internal structure reflecting ancient braiding.

Bed samples show predominantly rolling and graded suspension with one very well-sorted sand from graded suspension (QR segment) that was likely deposited at the end of the flood or during the dry season. This highlights the role of post-floods processes in the shaping of sandy landforms.
Two sandbars are composed of pure well-sorted graded suspension (QR segment). One sample had a high C value (coarse sand) falling in the QP segment, indicating high turbulence.
Three eroded bank samples fall in the PQ segment but with a better sorting, and are closer to the CM line than the pure OP samples.

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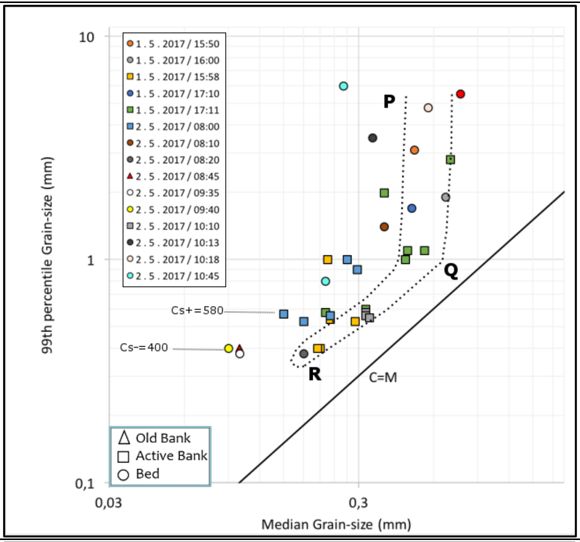

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Zone K: The results reflect a combination of CM processes and backwater effects associated with the Chindwin confluence.

Most bed samples show deposition associated with rolling and graded suspension.
Three bed samples include fine material associated with deposition after a flood.
All active bank samples plot within the graded suspension segment under medium turbulence, and include a coarser component associated with a mix of graded suspension and rolling. These features are common in the downstream zones and this may reflect a shift in patterns in the river.

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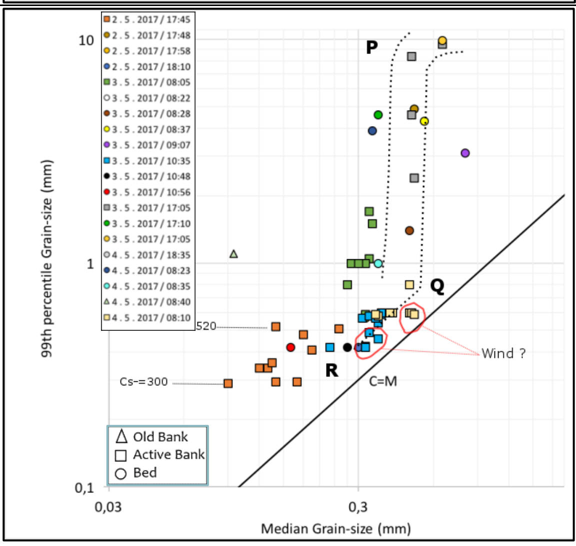

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Zone L: This reach shows similarities and differences with zone K.

Most bed samples fall in the PQ segment, as sand from graded suspension enriched in coarse sand or fine gravel.
Three sandbars were shaped in graded suspension deposits (QR segment) with C values comprised between 600 and 200 µm with similar grain-size to the bed samples, probably due to similar depositional processes.
A similarity with zone K is the presence of fine gravel (segment PQ) in two emerging bars, attributable to bedload rolling over upper bar platforms.
A difference with zone K is the very good sorting of a significant number of sand samples. This may be due to the velocity of the flow receding very slowly, which allows the finer particles to be winnowed out of the deposit, or it may be due to wind sorting over the flat bars.

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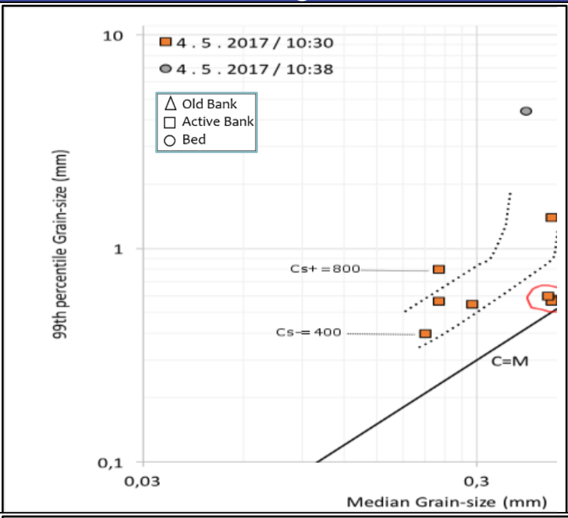
<tr><td>
</td>
<td>Zone M:

Two bed sites were sampled with the results falling within the PQ segment.
One site was sampled on a bar, with the sediments belonging to graded suspension (segment QR), except for one sample falling in the PQ segment. C values are comprised between 800 and 400 µm. As in zone K and L, the M value is scattered with both very good and poor sorting, consistent with wind action affecting the samples.
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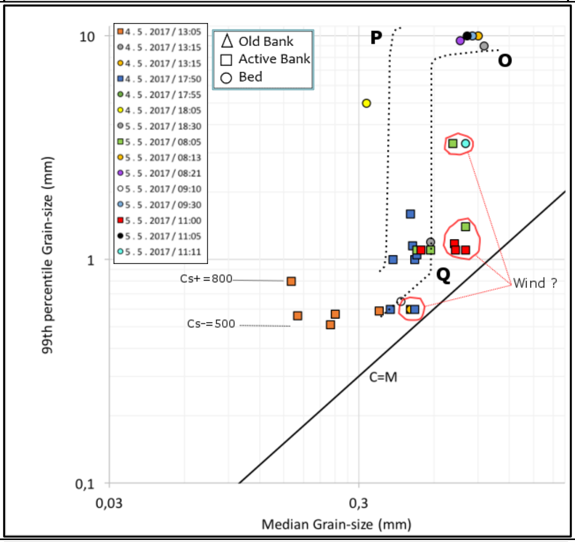
<tr><td>
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<td>Zone N: This zone shows similarities and differences with zones K and L.

Most bed samples plot at the upper limit of segment PQ and segment OP (rolling), with grain-sizes of sand and fine gravel.
Two bed samples were shaped by graded suspension and rolling (PQ segment): one is mixed, and one is enriched in fine sand.
The lateral sandbar samples show good sorting, and their placement on the CM image suggests they have been modified by wind action, with C values comprised between 800 and 500 microns.
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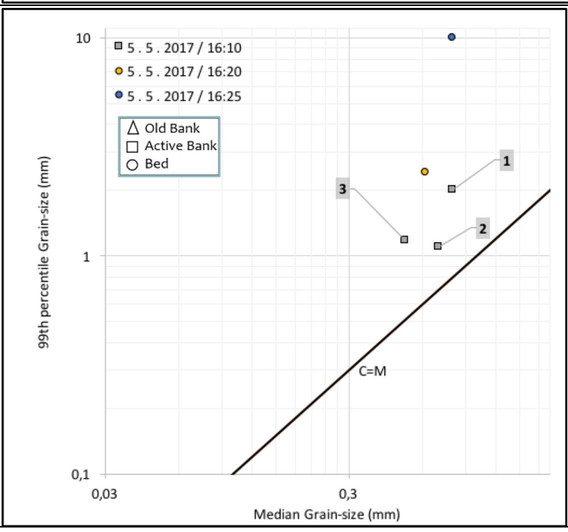
<tr><td>
</td>
<td>Zone O: This zone presents the same pattern as the previous ones, on a few samples.

The bar and the bed deposits fall in the PQ segment, indicative of rolling and deposition from graded suspension, with an enriched sandy matrix.
The active bank samples may have been affected by wind erosion since deposition at the end of the flood.
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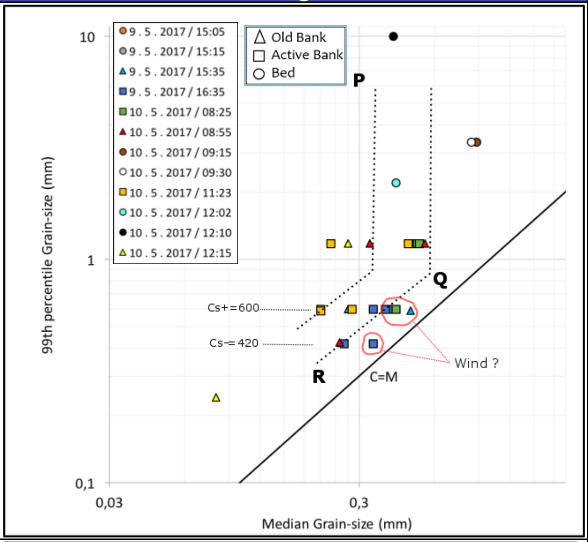
<tr><td>
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<td>Zone P: This zone is similar to zones K through N.

Six bed samples belong to the PQ segment; they are rich in sand which affects the median, at a constant value around 400 microns. But two of them are quite well sorted (M at 800 to 900 microns, C at 1200 microns).
Three active bars were sampled, with two of the bars derived from graded suspension and from suspension and rolling and the other from pure graded suspension.
One active bank sample was poorly sorted by sediment from graded suspension enriched in finer sand, with wind likely responsible for the sorting.
Samples from eroded banks display the same features as samples from fresh bars.
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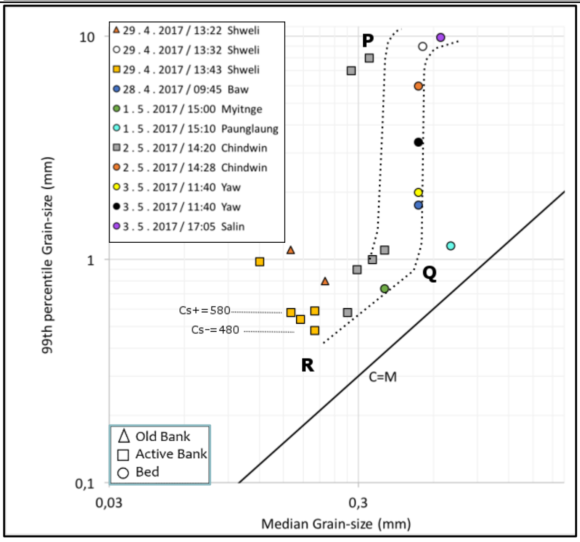
<tr><td>
</td>
<td>Zone Tributaries

Shweli — The sandbar is made of well-sorted sand deposited as graded suspension, except for a poorly sorted sample including coarse sand from a mix of graded suspension, suspension and rolling, and fine sand. The channel sample belongs to the PQ segment.
Baw, Myintnge, Paunlaung, Yaw, and Salin — Samples were collected from the bed only and are mostly composed of medium and coarse sand belonging to graded suspension, suspension and rolling.
Chindwin — The sampled bar displays two facies: a finer-facies from graded suspension and the finer part of PQ (S and R), and a coarser facies, in which the limit of PQ and OP is the rolling of particles close to 8 to 9 mm.
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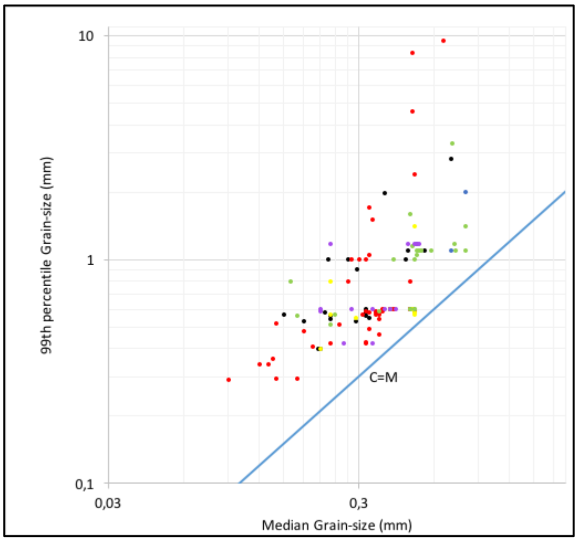
4.6.2 Synthesis of results

The CM results suggest that the transport processes captured by the sediment sampling in April/May 2017 can be used to identify two mega-zones within the river, consisting of zones A through J, and K through P.



All CM results from these groups are presented in

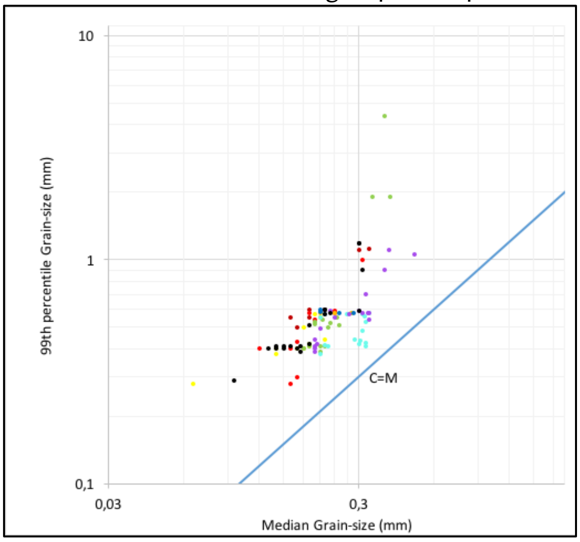


Figure 4.28:

- **Mega-zone 1**, from the headwaters of the Ayeyarwady through zone J. This group is characterised by sandbars and channel deposits derived from the bedload movement (rolling) of sand and fine gravel deposits. These were deposited following the peak of the flood season, and overlay coarser materials (gravels and cobbles) that are exposed during peak flows. The deposits are generally well sorted, plotting close to and parallel to the C = M line. The overlap between the composition of the coarse material on the active banks and in bed samples indicates that bedload transport over the inundated inclined surfaces of the lateral and mid-streambanks is an important sediment transport process. These banks were captured in samples collected from zones A, F, G, and J.
- **Mega-zone 2**, from zone K to P. River sediments in these zones are deposited by the same processes as occur upstream in mega-zone 1. However, there are significant differences, including:
    - Samples taken in terrestrial landforms have a considerably high content of particles deposited by rolling, showing a widespread continuum at the local scale between bed processes (rolling) and terrestrial landforms (bar platforms and active bars).
    - Landforms, both aquatic (bed) and terrestrial (platforms and active bars) display sediment spectra characterized by well identified processes (graded suspension, graded suspension + rolling), resulting in homogeneous well-sorted samples. However, the deposits are enriched in fine sand, probably trapped by landforms, vegetation and/or back water conditions created by the entrance of the Chindwin that facilitate a reduction in velocity and promote the deposition of this finer material. These processes would also create a positive feed-back mechanism creating low slopes in the area, with low slopes reducing water velocity and promoting deposition, which in turn reduces the slope of the river.

These results may also be linked to higher concentrations of suspended matter that can reduce the efficiency of sorting processes. The high sediment concentrations entering from mega-zone 1, combined with the additional sediment input from the Chindwin may result in an overloaded river with respect to sediment transport.

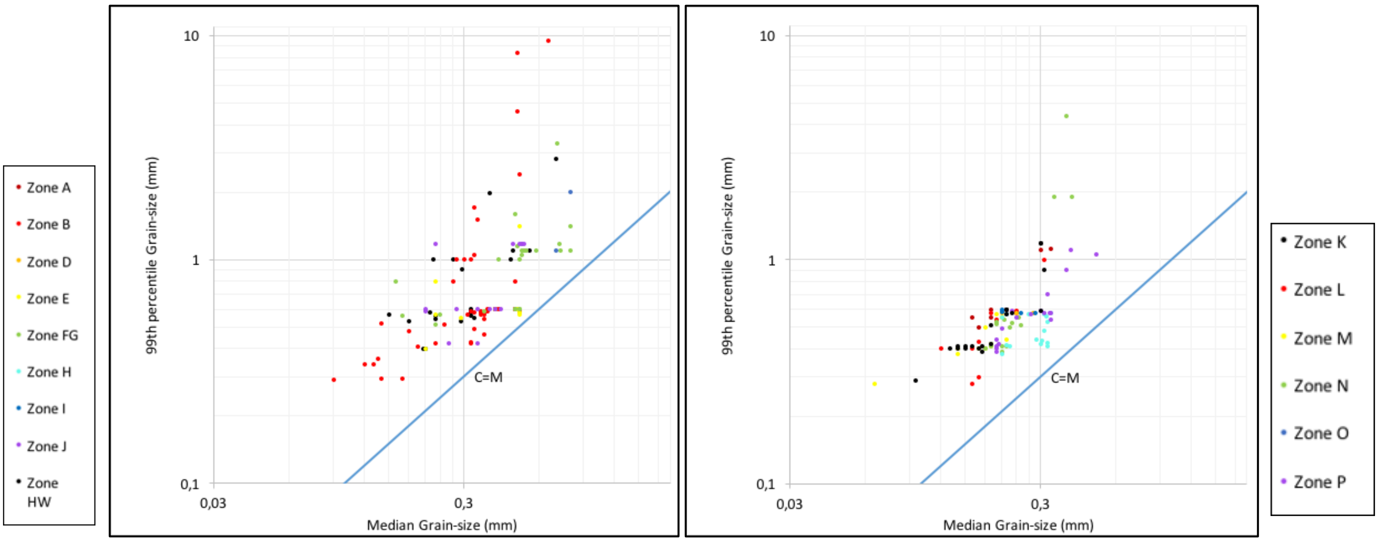


Figure 4.28 - CM results for 'mega'-zones identified in the Ayeyarwady. ***Results are for samples collected from the active banks***

The results also provide insights on a system-wide perspective. The continuity of grain-sizes in the CM graph was not considered as a normal feature by Passega (1964), who noticed the absence of certain sizes, generally ranging between 500 and 1,000 microns. This grain-size gap, studied along the Adige River in Italy, was attributed to the fact that grains slightly larger than those transported in suspension are the most difficult to roll and are soon abandoned by the current. Shaw and Kellerhals (1982) proposed another hypothesis. They showed that fine gravel is easily destroyed (crushed, notably) in the processes of transport because they easily roll or are trapped in the upper bed layer, while medium sand, transported in suspension, escapes this destruction. This is why in large rivers, especially in downstream reaches, fine gravel has disappeared from the sediment grain-size distribution, creating a sediment hiatus between sand and gravel.

Considering the Ayeyarwady, a hiatus between graded suspension units (segment QR) and segment PQ is apparent in the headwaters to zone J, but fine gravel does not disappear in the lower Ayeyarwady (zones K to Q), with samples plotting in the CM graph continuously between graded suspension and rolling.

This is consistent with the field observations and hypothesis that tributaries flowing seasonally from the hilly regions of the Dry Zone are able to transport these sediment fractions to the main trunk of the river, thus providing a source of coarser material. These lower zones also provide high concentrations of fines and thus a complete grain-size spectrum is present. The maximum Cs values support this hypothesis, with maximum C size decreasing between HW and I, consistent with the loss of fine gravels through physical erosion. In zone J, the Cs maximum increases and remains higher downstream, with peak values coinciding with zones M and N that flow through the heart of the dry zone.

Table 5. Maximum (Cs^+) and minimum (CS^-) values by geomorphic zone

	HW	A	B	D	E	G	H	I	J	K	L	M	N	O	P
Cs^+	600	600	600	480	470	450	480	580	700	600	600	800	800	600	600
Cs^-	300	480	280	320	380	380	280	560	380	400	200	400	500	420	500

4.7 Summary of Sediment Transport

A conceptual model of sediment transport in the Ayeyarwady was developed based on the sediment transport information gained through the field investigations and SOBA 3 investigations. This conceptual model includes the following components:

- The Ayeyarwady is a sediment-pulse system as much as it is a flood-pulse system. Sediment transport in the river is strongly skewed towards the peak flow season when water levels are high. In the Ayeyarwady the flood pulse may play an even more important role in the transport of sediments as compared to other Southeast Asian rivers, due to the low and continuous slope of the river from the confluence of the N'mai and Mali Hka to the sea. Due to these low slopes, the depth of the flood season flows plays a critical role in determining shear stress and hence sediment transport. Developments that alter peak flows have the potential to affect sediment transport for long distances downstream.
- Sediment input to the Ayeyarwady main stem is spatially and temporally heterogeneous. Types of sediment input include:
  - The basin upstream of Myitkyina and large tributaries in the upper and middle Ayeyarwady (Taping, Shweli, and Myitnge) provide high water inputs and sediment derived from the Shan Plateau and metamorphic belts in the northern catchment. These rivers likely produce resilient sands. This is consistent with the findings of Garzanti et al. (2016), who concluded that approximately 50% of the sand in the lower Ayeyarwady is derived from upstream of Mandalay. This is important as other areas of the catchment, such as the Chindwin, are commonly considered to be the major sources of sediment, and this is unlikely the whole story.
  - Downstream of the confluence of the N'mai Hka and Mali Hka rivers and, fine gravels are reduced in size through abrasion, resulting in a scarcity of this gain-size until the river flows through the Sagaing fault zone where coarser sediment is again present in the river.
  - The Sagaing fault zone is a major source of sediment, owing to the erodible hillsides and widespread land use alterations due to mining. Mining impacts occur on the riverbanks of the Ayeyarwady and in the tributary catchments in this area.
  - The Dry Zone downstream of the Chindwin is also characterized by erodible hillsides and land use practices that increase sediment input to the river. These hills are likely to contribute fine-and coarse-grained sediment with input linked to the episodic high rainfall events. Sediment is stored in the lower tributary and floodplain areas of the tributaries between these events.
  - The Chindwin, which unfortunately could not be included in the field survey, contributes large sediment loads, especially fine-grained material derived from the western ranges. Garzanti et al. (2016) suggested that the Chindwin provided the other ~50% of the sediment to the river, but the lower Dry Zone along the Ayeyarwady was not considered in the analysis. Due to the similarity in strata that exist in the Dry Zone in the Ayeyarwady and the Chindwin, it is very plausible that a large part of the 50% attributed to the Chindwin could potentially be derived from downstream of the confluence. This is consistent with the early observations of Stamp (1940) who documented large episodic inputs from tributaries in the Dry Zone downstream of the Chindwin.
  - Zones such as K and L are areas of sediment accumulation and reworking. Sediment transport through these zones probably exhibits a hysteresis, with the magnitude and extent of material transported dependent on the flow and sediment inflows from the previous year(s). For example, during a very wet flood season, large volumes of sediment will be transferred through zone J, and stored in zones K and L. These sediments will remain until either another sufficiently high flow occurs for transport, or they are physically eroded *in situ* to the point that the flow rate can transport the material.
  - The presence of fine-grained sands overlying gravels at the end of the dry season highlights the seasonal variability of bed materials in the river. These seasonal changes need to be recognized when considering the provenance or energy regime of the river. Bed sampling

conducted over the wet season would undoubtedly produce very different results. This also raises questions about using these sediment samples as the basis for sediment transport modelling, as they would not reflect the sediment transported during peak wet season, which is when most sediment transport occurs.

  - A good analogy for sediment transport in the Ayeyarwady is a series of conveyor belts operating at different speeds and delivering different quantities of sediment. The headwater and upper Ayeyarwady input act as a belt moving at a fairly continuous speed and delivering a uniform annual input. The tributaries near the Sagaing fault and in the dry zone transport sediment move much more quickly, but in a more episodic pattern, owing to sediment production being linked to land use activities and sediment transport being linked to rainfall patterns. These inputs can act as fast-moving conveyor belts that operate episodically. The main stem of the Ayeyarwady has a much lower slope as compared to the tributaries, and acts as a slow-moving conveyor belt, with sediment transport linked to the continuous and episodic inputs. These processes can form an infinite number of sediment transport combinations, as transport at any one time within the Ayeyarwady is governed by land use and rainfall patterns spanning many years.

- The Ayeyarwady carries silt and clay and commonly appears very muddy. Even the low TSS values collected in April and May (<100 mg L^{-1}) were sufficient to make the river opaque and give it a strong brown colouration. However, these fine grain-sizes are efficiently transported through the river once in suspension, and are largely absent from the bank, bar, and bed deposits in the river, which are dominated by sand. Sediment transport in the Ayeyarwady should be considered as two systems, fine- and coarse-grained, to understand how the river will be affected by land use changes and water resource developments. Sand and coarser material are more efficiently trapped in impoundments as compared to silt and clay, so these sediment loads are more susceptible to change as compared to the finer load.

- The export of large volumes of fine-grained material to the coastal region combines with the local long-shore currents to maintenance the and coastal areas far removed from the mouth of the Ayeyarwady, and underpin coastal productivity.

- Collectively, these processes combine to produce a river system that is heterogeneous with respect to sediment input and transport, and dependent on land use practices, rainfall patterns, rainfall intensity, and maintenance of a strong flood pulse.

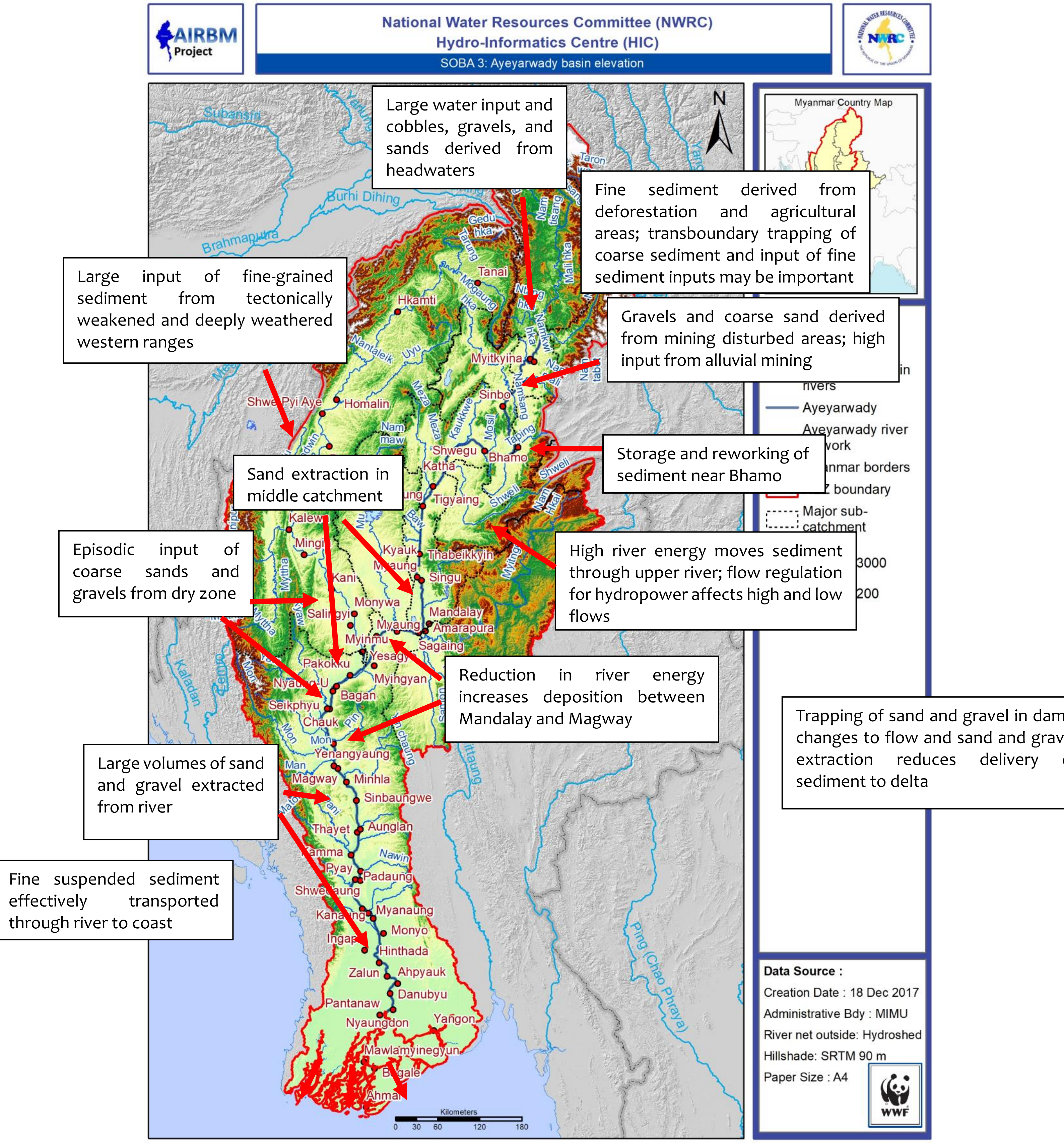


Figure 4.29 - Schematic summary of sediment provenance and transport based on SOBA 3 observations, field results and literature. *These processes are indicative only and monitoring is required to verify*

4.8 Estimates of Sediment Budgets

The lack of current and reliable sediment transport measurements precludes the ability to derive a reliable sediment budget for the Ayeyarwady. In some ways, this is advantageous, as it forces a consideration of how fine, sand and gravel sized material moves through the system, and the landscapes from which they are derived.

4.8.1 Published sediment transport values

Historic sediment transport information from Seiktha, near the head of the Ayeyarwady Delta was collected from 1877 to 1878 by Gordon (1885), who estimated an annual sediment load of 340 Mt yr^{-1} for the year, but adjusted the figure to 261 Mt yr^{-1} based on a revision in the discharge volumes of the river during the monsoon. Using the flow/sediment relationship derived from the monitoring results, sediment loads ranging from 248 Mt yr^{-1} to 352 Mt yr^{-1} have been subsequently calculated for the period of 1869 to 1879 (Robinson et al., 2007).

Stamp (1940) published monthly sediment load values based on Gordon's annual average load of 261 Mt yr^{-1} showing that ~66% of the sediment load was delivered from July to September, and ~87% from June to October. Stamp (1940) also provides a rough sediment budget for the basin, although the basis for the values are not well documented (Table 6). The budget suggests that less than 15% of the total sediment load was derived from upstream of Mandalay, with over 85% from the Chindwin and remaining dry belt.

Table 6 - Sediment budget as determined by Stamp (1940), based on Gordon's estimate of 261 Mt yr^{-1} for the river at Seiktha

Location/Source	Annual Sediment Load (Mt yr^{-1})
Mandalay	32 (12%)
Chindwin	109 (42%)
Central Dry Belt, excluding Chindwin	120 (46%)

Robison et al., (2007) measured suspended sediments in the Ayeyarwady and Thanlwin rivers from 2005 to 2006, and used the findings to re-analyse Gordon's suspended sediment dataset. They found that Gordon's estimate was likely low due to the loss of very fine-grained material during filtration, and suggested a revised 19th century sediment load of 364 ±60 Mt yr^{-1} for the Ayeyarwady. Furuichi et al., (2009) derived a sediment budget of 325±57 Mt yr^{-1} based on measurements at Pyay between 1969 and 1996, and estimated sediment yields over the catchment at 955 ± 166 t km^2yr^{-1}. This yield is considerably higher than that suggested by Milliman and Syvitski (1992) of 620 t km^2yr^{-1}, with the source of this value based on run-off, topography, and comparisons with other river catchments.

Table 7 - Estimated sediment loads, denudation rates, and sediment yields in sub-catchments in the Ayeyarwady based on mineral provenance and geochemical and geochronological signatures

Catchment	Sediment input (Mt yr^{-1}) % based on load of 375 (Mt yr^{-1})	Denudation rate millimetres per year	Sediment yield (t km^{-2})
Nmae	60 to 70 (~17%)	0.5	1,300
Mali	60 to 70 (~17%)	0.5	1,300
Taping	10 (~3%)	0.5	1,000 to 1,500
Sweli	30 (~8%)	0.5	1,000 to 1,500
Mytinge	5 (~1%)	0.1	200
Chindwin	200 (53%)	0.7	1,700
Total for catchment	**365 to 385**	**0.3 to 0.4**	**~1,000**

(Garzanti et al., 2016)

A recent investigation by Garzanti et al., (2016) used the provenance of heavy minerals and the geochemical and geochronological signatures of bedload sand in the Ayeyarwady to estimate the relative contributions of sand from different sub-catchments. The study estimated sediment fluxes and denudation rates for the sub-catchments based on an estimate of 325 to 364 Mt yr^{-1} of suspended sediment and an assumed additional

10% contribution from bedload. This approach assumes that the suspended load and bedload have similar ratios of minerals, which Garzanti et al., (2016) suggest is a reasonable assumption, although the finer-grained mineralogy of the Chindwin is identified as a potentially complicating factor.

The analysis suggests that approximately half of the sediment load in the Ayeyarwady is derived from the Chindwin catchment, with the headwater rivers of N'mai and Mali Hka collectively contributing an additional ~35%. The remaining sub-catchments contribute an estimated <15% of the total annual sediment load.

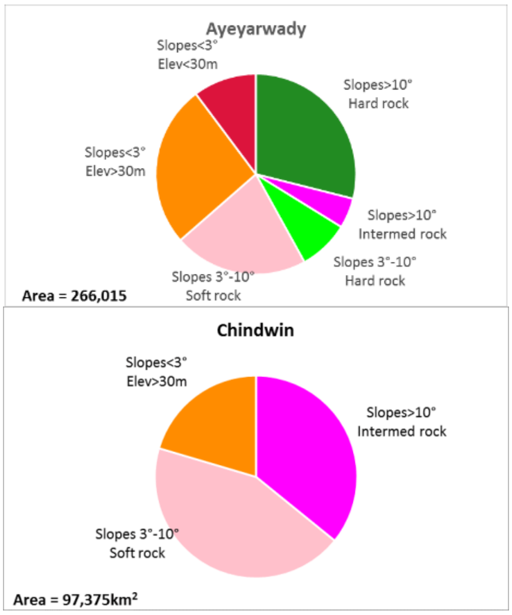
4.9 Discussion and Interpretation of Sediment Transport Information

Interpreting and integrating the published sediment transport information with field observations and the literature provides the following insights:

- The often-cited Gordon sediment values are invaluable for providing a baseline, but the methodology used to collect the samples has shortcomings that need to be recognized, including:
  - The method used to collect the samples (an open tube deployed horizontally in the river) has been demonstrated to not collect representative samples;
  - The tube presumably collected the same volume from each depth, so sediment carried in slower-moving surface waters would have been overrepresented and sediment in fast-moving deeper waters underrepresented;
  - The laboratory methods were inadequate to capture all of the suspended sediment (Robinson et al., 2007).
- The sediment yield estimates of Furuichi et al., (2009) are based on sediment loads derived from rating curves of unknown origin (and possibly the same ones in use today) so the veracity of the results is unknown and highly questionable.
- The work of Garzanti et al. (2016) focuses on sand and may not hold true for the silt component. The work also limited consideration of sediment input to the upper Ayeyarwady and the Chindwin. This is in contrast to Stamp (1940) and the recent SOBA 3 observations, which show that considerable sediment inputs are derived from the dry zone downstream of the Chindwin.

Considering these issues, presented below is a hypothetical sediment budget for silt and sand + gravel inputs from three areas of the catchment (the upper Ayeyarwady and tributaries upstream of the Chindwin; the Chindwin; and the lower Ayeyarwady downstream of the Chindwin) that recognizes what is known about sediment transport. This is only hypothetical and provided as an example. There are many combinations of inputs that could satisfy the observations, and until and unless actual sediment transport rates and sediment grain-size characteristics are measured in the river over a range of flow conditions, establishing reliable sediment models will not be possible.

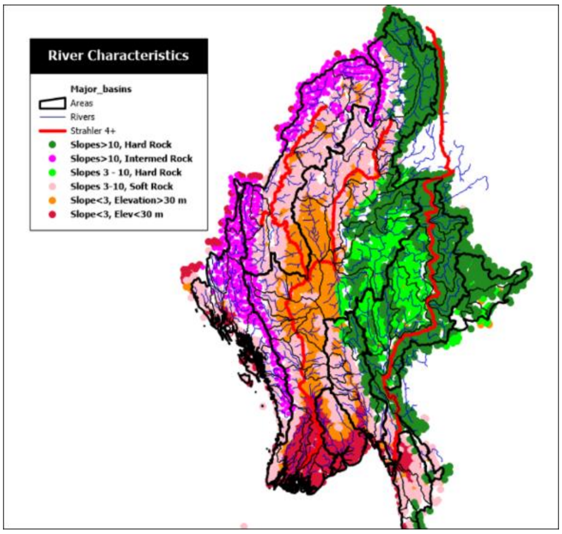
For the hypothetical example provided below, the estimates of sediment yield are based on the distribution of physiographic/geomorphic areas within the Ayeyarwady and the Chindwin (

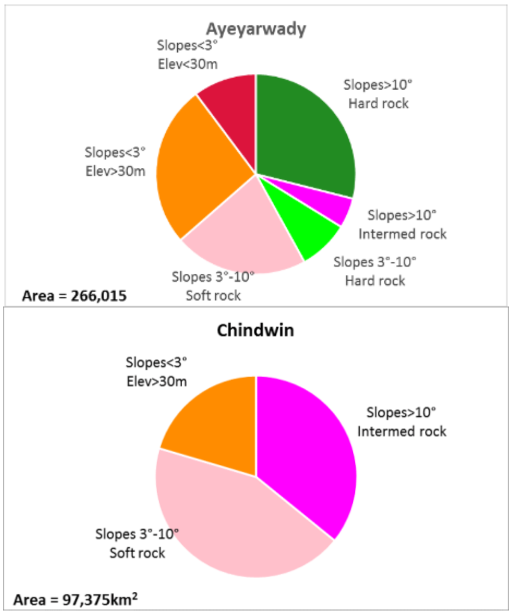


Unit	Estimated Sand and Gravel Yield (t km^{-2}yr^{-1})	Estimated Silt Yield (t km^{-2}yr^{-1})	Comments
Slopes >10, hard rock	700	300	Confined to upper Ayeyarwady, crystalline bedrock is likely to produce large quantities of sand, albeit at a relatively slower weathering rate as compared to other units.
Slopes >10, intermediate rock	600	1,200	Assumed to have a very high weathering rate, due to high rainfall and deep weathering of tectonically weakened area. Substantial portion of load is likely to arrive in episodic events.
Slopes 3 to 10°, hard rock	200	200	These crystalline areas are typically intra-plateau areas with relatively low rainfall, compared to other areas of catchment. The relatively low slopes and crystalline strata limits sediment input.
Slopes 3 to 10°, soft rock	300	300	Erodible and exposed areas neighboring the lower Ayeyarwady and Chindwin main stems; sediment input is likely tied to episodic events.
Slopes <3°, elevation >30 m	0	0	These flat lying areas are predominantly areas of sediment storage and reworking; volumes of new sediment derived from these areas are low.
Slopes <3°, elevation 30 m	0	0	This Deltaic area is considered depositional.

Figure 4.30), and an assumed sediment yield and division between silt and sand + gravel derived from each unit. The relative differences between the units reflect the tectonic characteristics and hydrology of the region.

These are very simple estimates that assume that the sediment input from each unit is uniform within the unit, and do not take into account the role of land use in sediment supply.





Unit	Estimated Sand and Gravel Yield ($t\ km^{-2}yr^{-1}$)	Estimated Silt Yield ($t\ km^{-2}yr^{-1}$)	Comments
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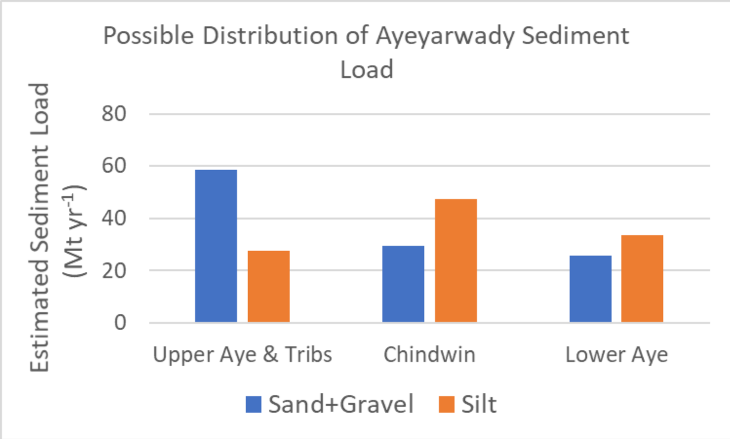
Slopes <3°, elevation >30 m	0	0	These flat lying areas are predominantly areas of sediment storage and reworking; volumes of new sediment derived from these areas are low.
Slopes <3°, elevation 30 m	0	0	This Deltaic area is considered depositional.

Figure 4.30 - Physiographic / geomorphic units identified in Myanmar, and the distribution of the units in the Ayeyarwady and Chindwin catchments *(Source: ICEM, 2017)*

When distributed over the appropriate areas in the catchments, the resulting sediment load is ~220 Mt yr^{-1} with a catchment yield of ~613 t km^{-2}yr^{-1}. These are within the bounds of the previously presented estimates. The proportion of silt and sand+gravel provided by this simple sediment model are shown by source and



sediment component in

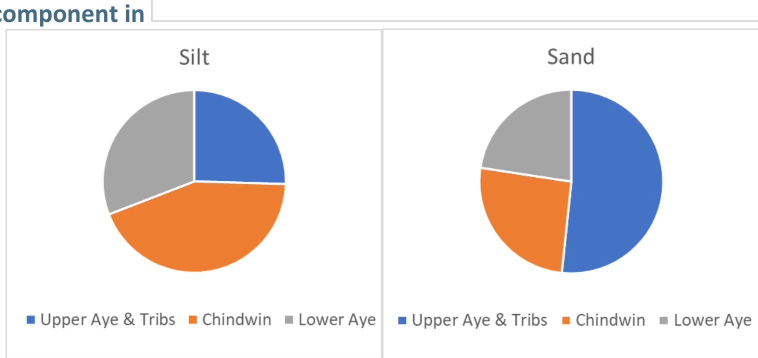


Figure 4.31. These estimates show the following characteristics:

- The upper Ayeyarwady and the Chindwin each input about 35% of the total sediment load, with the lower Ayeyarwady contributing the remaining. This is likely an overestimate of input from the lower catchment, however the increased rainfall and inflows in the lower catchment will contribute to increase sediment loads.
- About half of the sand is derived from the upper Ayeyarwady with the remainder split almost evenly between the other two areas. This is consistent with Garzanti et al., (2016), if the Chindwin input identified using the sand provenance is divided between the Chindwin and the lower Ayeyarwady.

The majority of silt is derived from the Chindwin, with only ~25% of the silt load derived from the upper Ayeyarwady. This is consistent with observations of the Chindwin by Stamp (1940), and the darker water that is frequently observed at the confluence (

- Figure 4.32).
- These estimates do not reflect likely reductions in sediment load associated with sediment trapping in hydropower or irrigation impoundments.

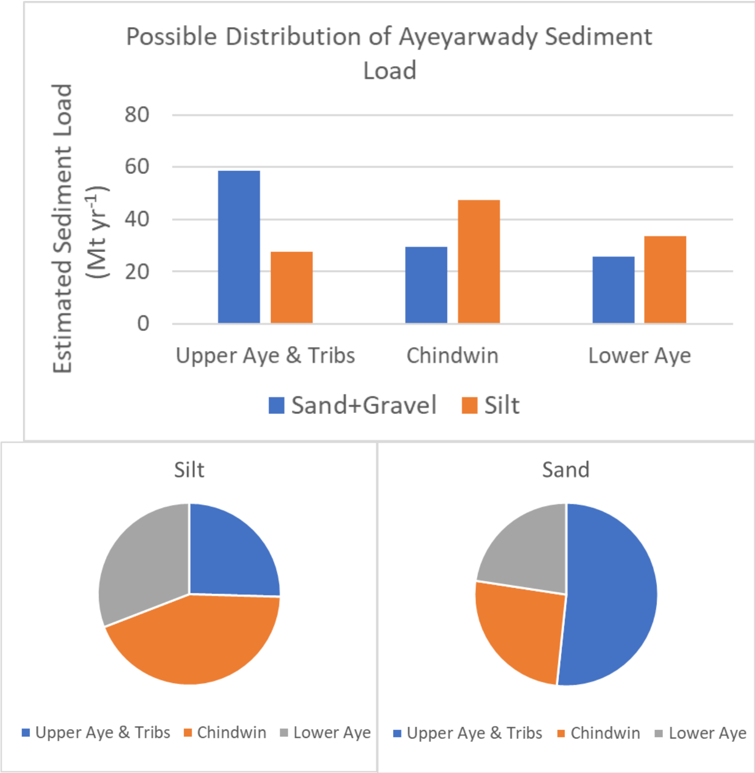


Figure 4.31 - Distribution of sand and silt from the upper Ayeyarwady, Chindwin and lower Ayeyarwady based on the distribution of physiographic / geomorphic regions and assumed sediment yields

Figure 4.32 - Google Earth image showing sediment rich Chindwin mixing with the Ayeyarwady during the dry season, January 2017.

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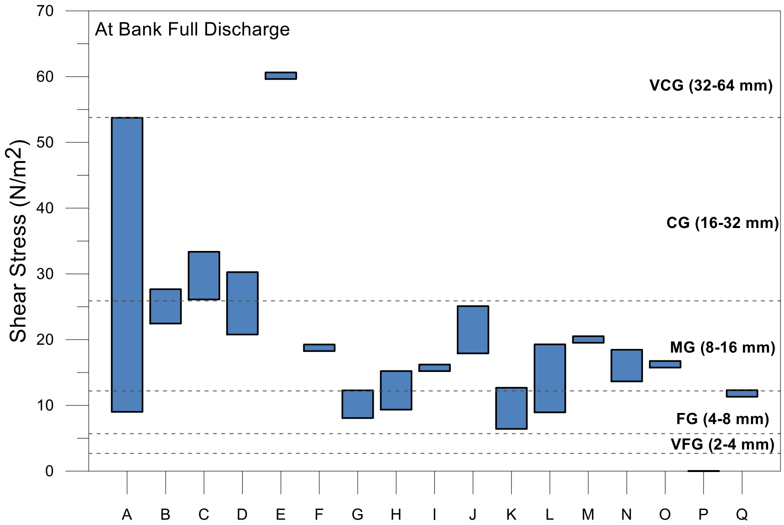
Achieving sediment inputs that are compatible with the findings of previous investigations highlights the necessity of having very high sediment yields from the steep, tectonically active regions of the Chindwin and lower Ayeyarwady to achieve the 50% of sand input and the majority of silt input. The abundance of silt purportedly transported by the river is interesting, in that there was very little silt present in the bed or bank samples collected during the SOBA 3 field campaign. On a few sandbars and banks there were minor silt and clay deposits in small back waters, but in general, the sediment deposits are clay and silt free. This suggests that silt is efficiently transported through the river, which is consistent with the energy calculations



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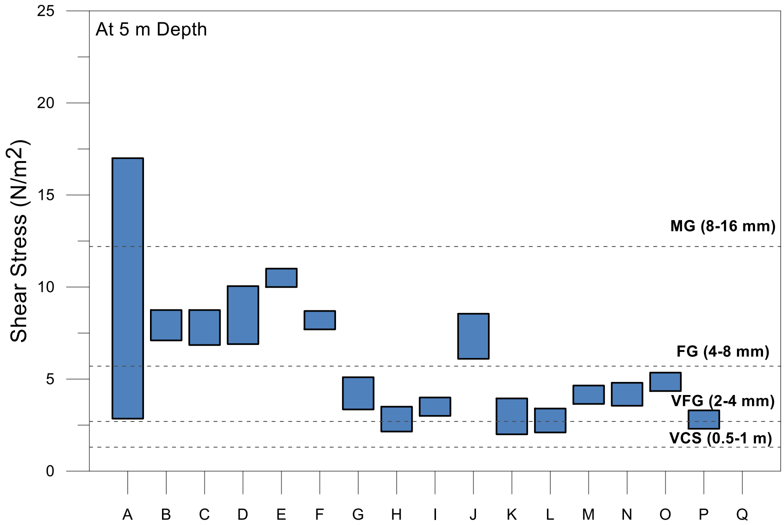


Figure 4.26. Its lack of storage is consistent with the material being maintained in suspension and transported through the river to the delta within the same season. This highlights the need to understand silt and sand + gravel transport independently, as it is the sand + gravel budget that is important with respect to channel and bank stability.

It must be stressed that these types of exercises can provide insights into the sources and relative contribution of sediments, but unless and until there are actual data to guide the development of these types of models, they cannot be relied upon.

5. ISSUES RELATED TO GEOMORPHOLOGY

5.1 Overview of Issues and Risks

All physical aspects of the Ayeyarwady River and its catchment are related to the geomorphology and sediment transport of the river. Rivers will adjust to any change to the magnitude, frequency, duration, rate, or seasonality of water or sediment inputs. These adjustments include changes to the elevation or slope of the riverbed, alteration to riverbanks through erosion or deposition, changes to the shape or channels, and even changes to the large-scale course of the river. Under natural conditions, rivers are continually adjusting to the inherent variability of interactions between the climate and the landscape. The dynamic equilibrium between the land and climate creates an ever-changing riverscape that hosts a wide variety of physical attributes that underpin the habitats supporting biological diversity. Any change to the physical (land use, tectonics, and channel alterations), climatic (climate change and El Niño Southern Oscillation), or hydrological attributes (flow regulation, irrigation, and alteration to runoff and infiltration) of a river will alter the geomorphology and sediment transport processes occurring within the system.

Landscape and hydrologic changes alter rivers continuously, but these natural responses are considered impacts when they alter the way that humans use and interact with river systems. Changes such as bank erosion, channel filling or deepening, delta instability or subsidence are all geomorphic changes that reflect the natural response of the river system, but can also affect the ecological, social, economic, and cultural uses of the waterway.

In the Ayeyarwady, identified issues include:

- **Bank and channel morphology and stability** — The physical attributes and condition of the banks and bed are important for maintaining the connectivity of the river channel, for supporting and protecting the infrastructure developed along the river (roads, bridges, irrigation pumps, and shipping facilities) and critical for safe and efficient navigation. The maintenance of bank stability and channel capacity are also important for flood prevention and the maintenance of floodplains. The Ayeyarwady is a highly active river, and the SOBA 3 investigations have mapped channel changes throughout the river. The geomorphic zones most susceptible to change are the broad alluvial areas with low slope, in which sediment deposition and reworking are constantly occurring (gray channel in Figure 5.1, as indicated). Instability and changes in these areas can be driven by hydrologic or land use changes, such as mining, damming, sediment extraction, and water extraction, some of which are also indicated in Figure 5.1. The relationship between these pressures and channel stability was discussed in Section 3 (Catchment activities) with additional information and discussion provided in the Trend Analysis (Section 5.3). The findings of SOBA 3 provide strong support for a changing river. However, the important question is whether the river is changing within a range which will continue to support the key ecological and social systems dependent on the river, or if the geomorphic processes are approaching, or have already passed, thresholds that will alter the river's fundamental character.

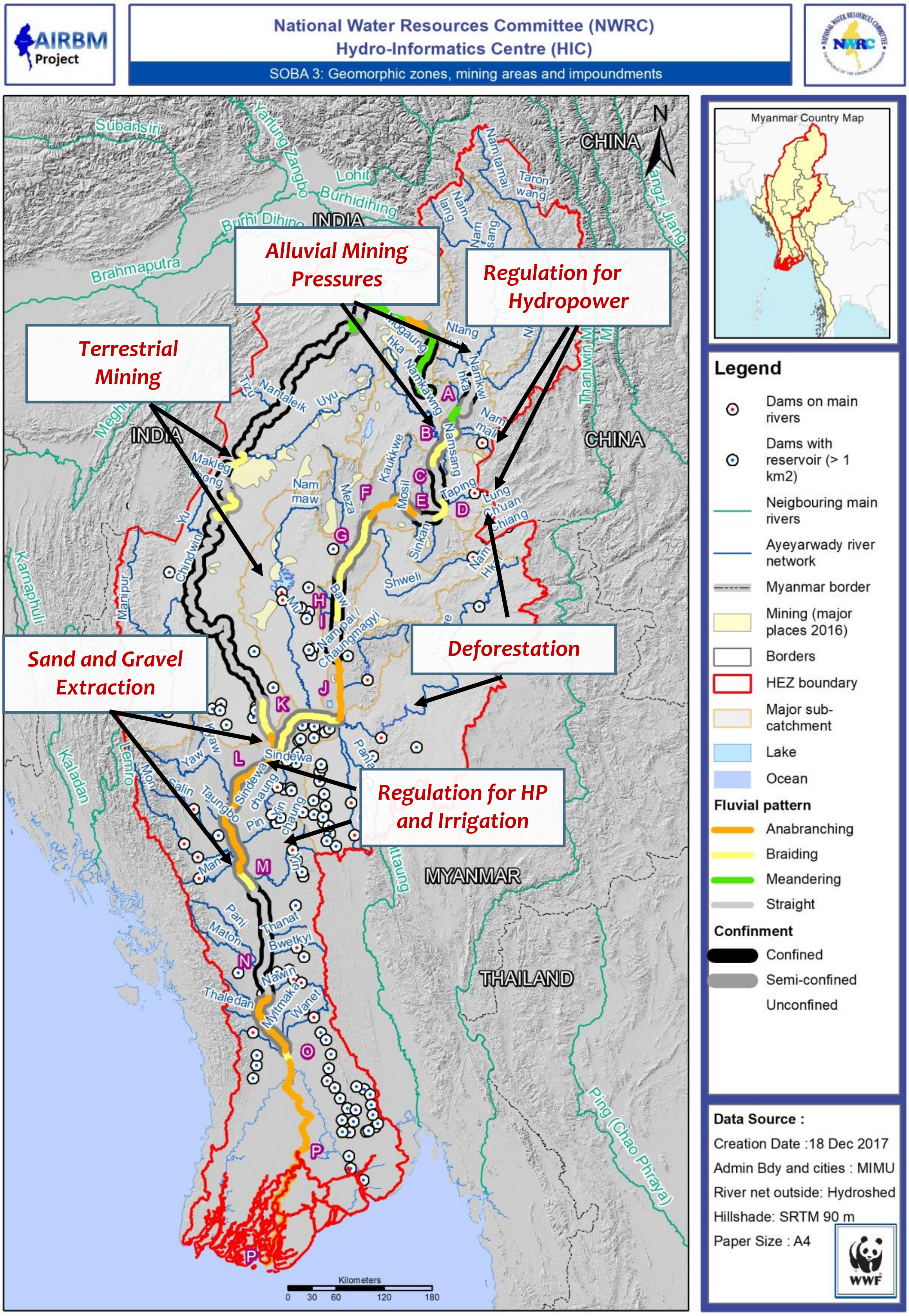
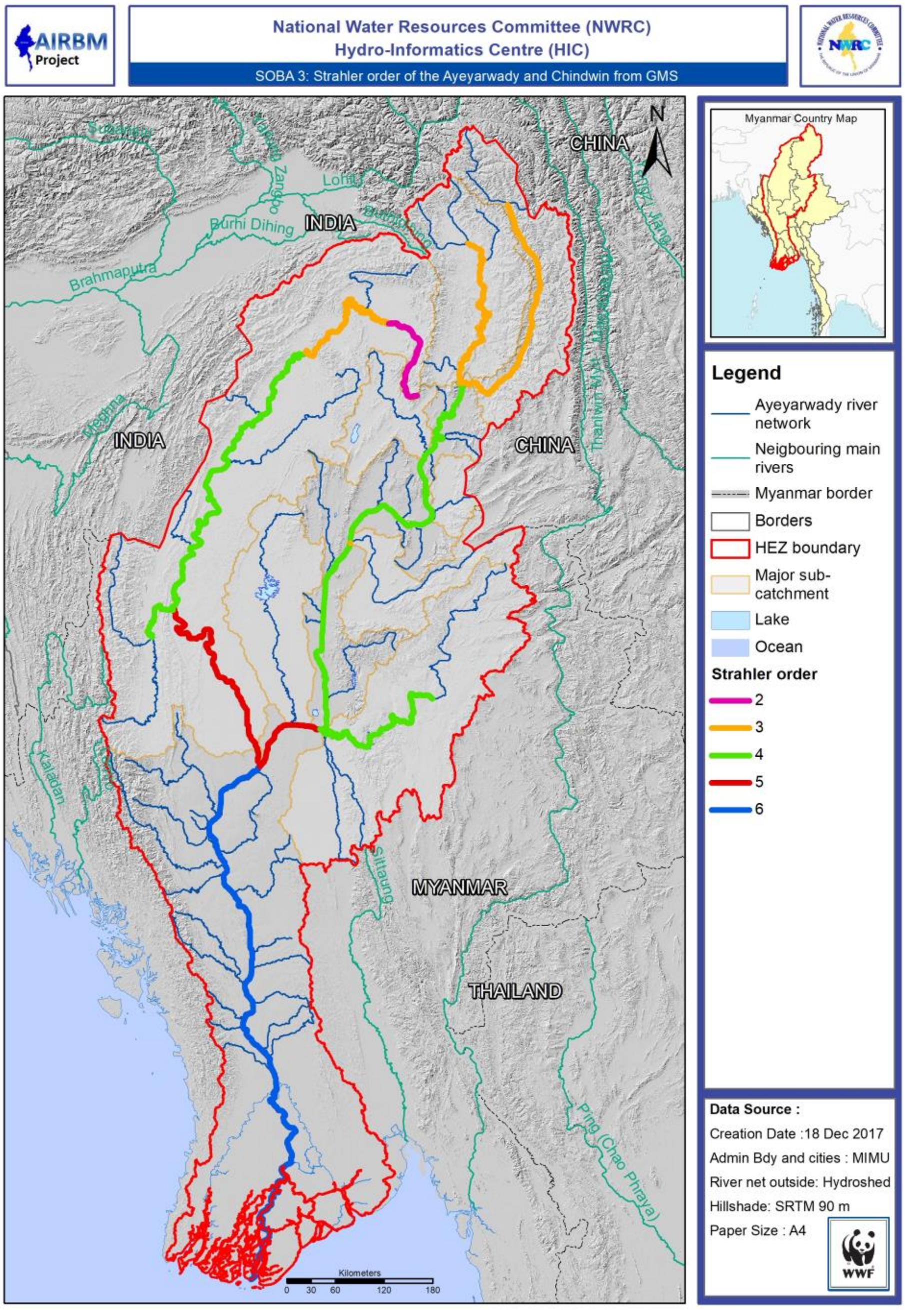


Figure 5.1 - Ayeyarwady River showing river land use pressures

Note that arrows are indicative only with all activities dispersed throughout the catchment.

Sediment transport and river connectivity — The movement of material through the river controls the channel and bank characteristics, and nutrient dispersal and availability, which is relevant to biodiversity, fisheries, and the important economic sectors of agriculture and construction. Nutrient transport is not a geomorphic process per se; however, the inextricable link between sediment and nutrients needs to be recognised and considered in basin planning. Altering the magnitude, and/or timing of sediment movement with respect to hydrologic patterns, or the characteristics of the material moving through the system (grain-size, mineralogy and nutrient content) will translate into changes in the physical and biological attributes of the river. The integrity of river systems is dependent on the maintenance of the continuity of sediment supply and delivery. In this context, retaining the connectivity of high-order Strahler rivers (



- Figure 5.2) is paramount, as they are the major conduits through which all other smaller rivers are connected to the delta and coast.

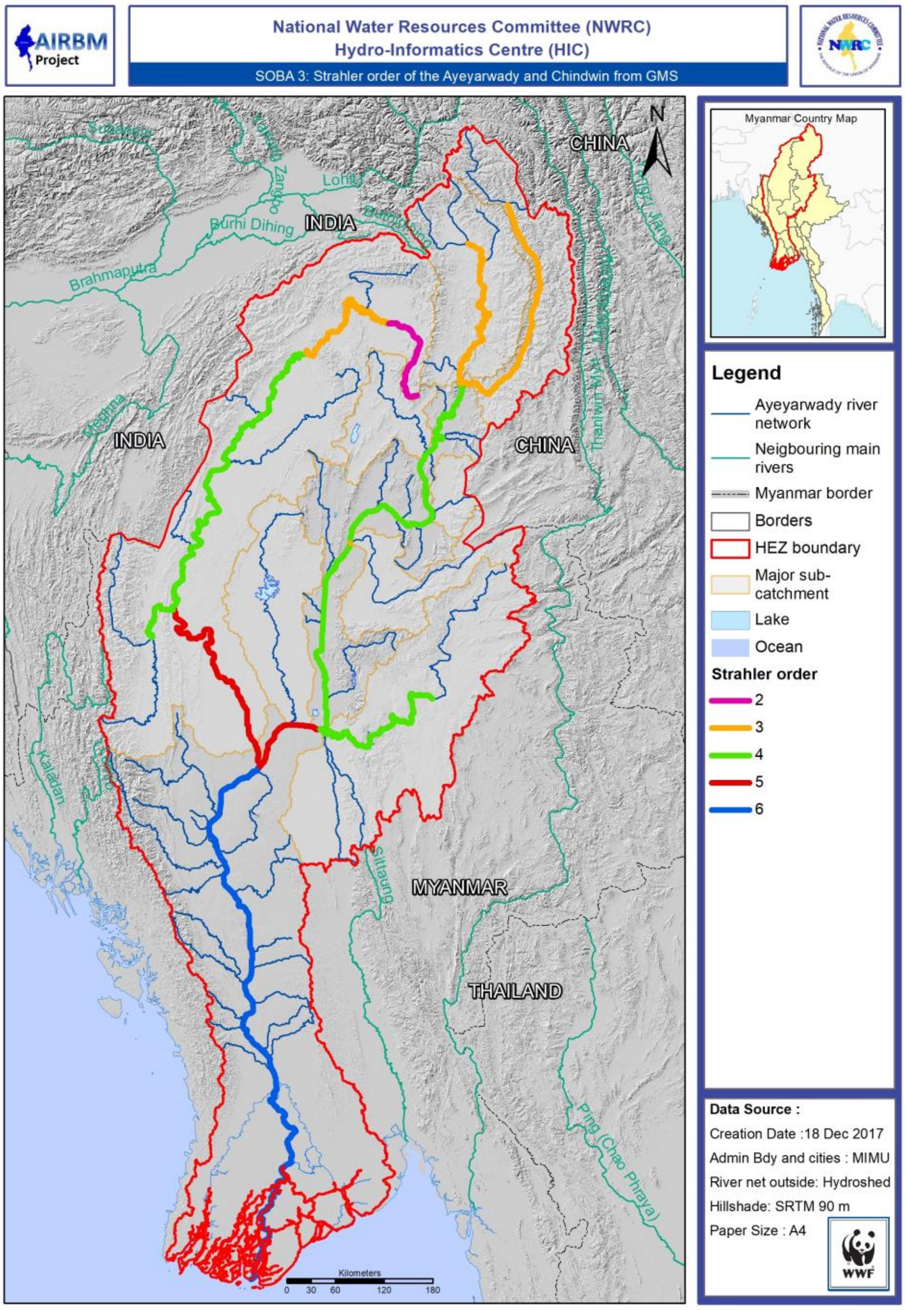
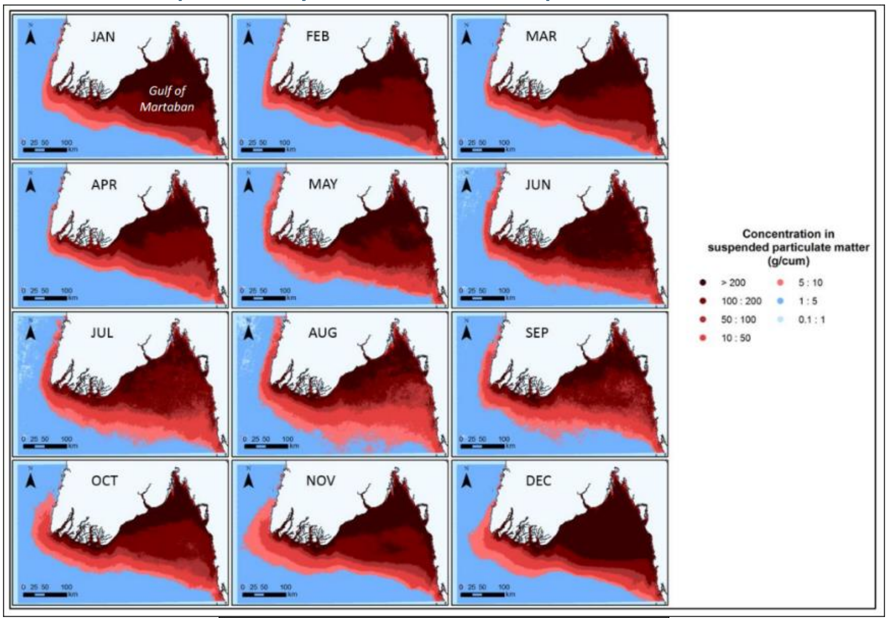
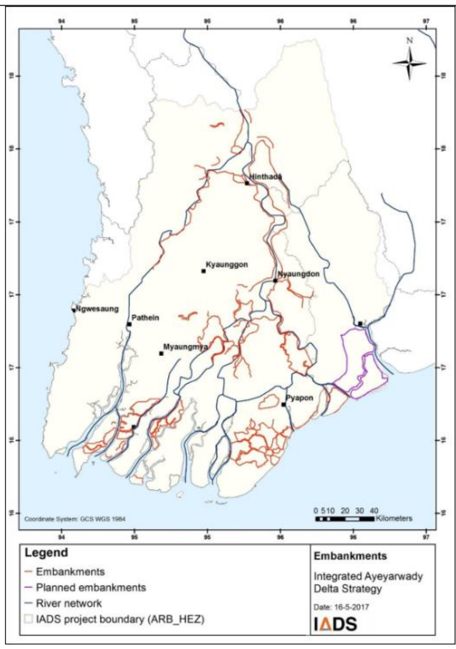


Figure 5.2 - Connectivity throughout the high-order Strahler rivers of the Ayeyarwady

Maintenance of the Ayeyarwady Delta — River deltas are the culmination of all processes occurring in the upstream catchment, and the interface between the terrestrial, fluvial, and marine environments. On a physical level, deltas are created and maintained by the delivery of sediment from a river to the coast, and maintaining sediment supply is critical for maintaining delta stability. If sediment delivery is reduced, deltas will contract and sink. Sediment supply to the coast is also required to maintain the productivity of coastal areas and provide sediment for more distal areas (





- Figure 5.3). Deltas and resilient coastlines provide protection against floods and typhoons, host a wide range of ecological habitats, and provide fertile land for agriculture and coastal areas for urban development and recreation. The Ayeyarwady Delta is the most densely populated area of the river catchment and supports a population of almost 15 million people (including Yangon, Anthony et al., 2017a). Worldwide, deltas are at risk due to increased erosion associated with the disruption of upstream sediment supply, combined with climate change, ground water extraction, mangrove removal, and coastline modifications.

Activities that have the potential to affect the geomorphology of the delta include the alteration of sediment supply, due to trapping in upstream dams and sediment extraction, and alterations to the pattern of flow delivery, including groundwater extraction, channelization of the distributaries, and climate change.

A summary of the issues and pressures discussed above, which are potential indicators for establishing present trends and monitoring future changes is provided in Table 8.

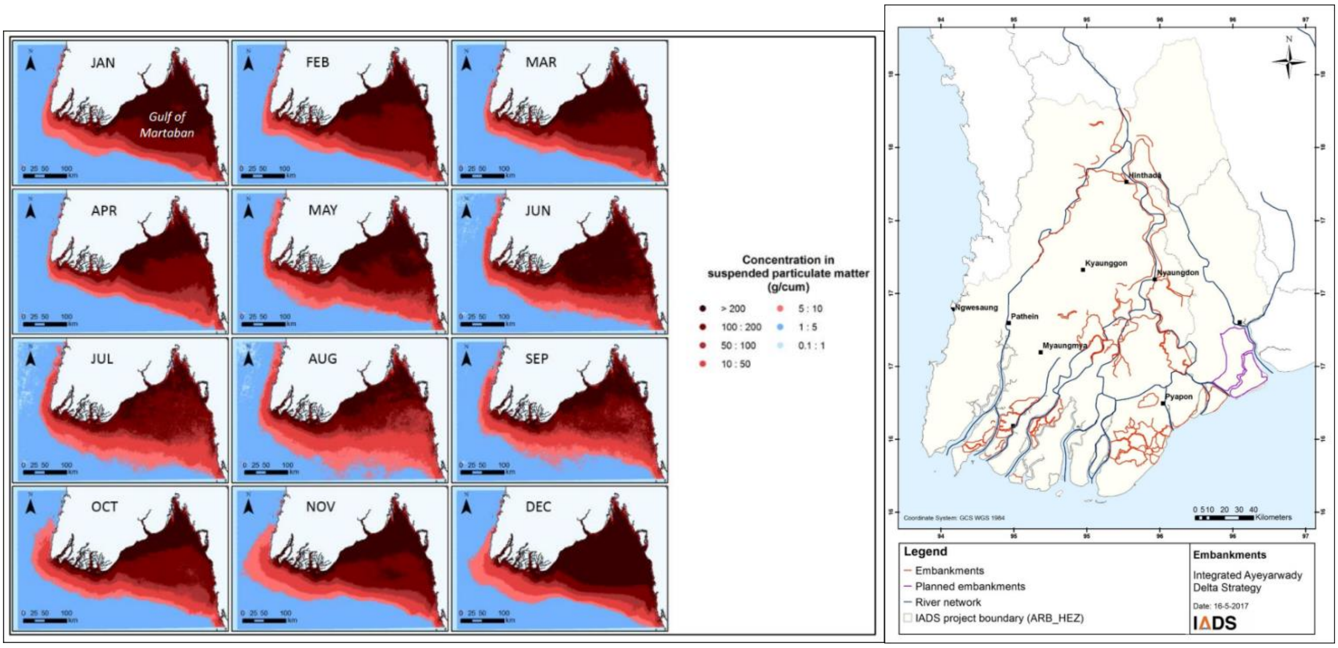


Figure 5.3 - (Left) suspended particulate matter in the coastal zone of the Ayeyarwady Delta, Edward *et al.,* 2017), and (right) Map showing extent of river embankments in the Ayeyarwady Delta. *(IADS, 2017)*

Table 8 - Summary of SOBA 3 issues and potential indicators

PACKAGE	THEMES	PLANNING ISSUE/PRIOIRTY	INDICATORS
SOBA 3	**Sediment transport and fluvial geomorphology**	**Bank and channel stability and mobility, including erosion/deposition and channel aggradation/degradation**	Annual and seasonal sediment loads at key sites Annual and seasonal flow at key sites Timing of sediment and flow delivery (% per month) at key sites Dry season/wet season channel cross-sections Rates and extent of channel migration over time Volumes and grain-size of sediment extracted by major sub-catchment Percentage of catchment upstream of dams by major sub-catchments Rates of deforestation Areas disturbed by mining activities
		Sediment and nutrient transport	Annual and seasonal season sediment loads Wet season/dry season nutrient loads Water clarity Wet/dry season sediment grain-size Nutrient content of sediments
		Delta maintenance and stability	Annual and seasonal season sediment loads Wet season/dry season flow Channel morphological changes (lateral erosion or bathymetrical) Sediment extraction Coastline evolution/mangrove loss Groundwater extraction/delta subsidence Sea level rise

5.2 Evaluation of Indicators for Trend Assessment

The indicators identified in Table 8 are listed in Table 9, along with a more detailed description of the data needs and an assessment of the data availability and quality, based on the SOBA 3 investigations and assessment. It should be noted that SOBA 3 has been limited in duration; while the applicable datasets were requested by the SOBA 3 Team, and many datasets were provided by the Project Management Unit, there are possibly additional datasets that are relevant to the assessment of the indicators that have not been obtained.

Where possible, potential surrogates were identified in the case that primary information was not available. For example, the SOBA review of discharge gauging sites (Walker, 2017) concluded there are potentially large errors associated with the conversion of water level to discharge. Recognising this, the water level data at the sites provided by the DMH were analysed as a surrogate for the discharge results.

In the following sections, trend analyses are presented and discussed, for the indicators identified as either 'Yes' or 'Partially' suitable for trend analysis. These indicators are also highlighted in the following table. By necessity, many of these assessments are qualitative at this stage, but can still provide an indication of likely trend directions.

Table 9 - Indicators, data requirements and preliminary assessment of data availability

Indicator	Data Required	Preliminary Assessment of Data Availability and Quality	Suitable for Trend Analysis
Annual and seasonal flow at key sites	Accurate flow measurements, accurate water levels can be used as qualitative surrogate	Poor flow data, good water level data at gauging sites	Partially
Annual and seasonal sediment loads at key sites	Accurate flow and sediment measurements	Poor quality	No
Dry season/wet season channel cross-sections	Repeat channel cross-sections at fixed locations	None available in time frame of SOBA 3	No
Rates and extent of channel migration over time	Image/GIS analysis	Good coverage between 1988 and 2015	Yes, but difficult to quantify
Volumes and grain-size of sediment extracted by major sub-catchment	Accurate records of sediment extraction	SOBA 3 Survey provides qualitative assessment	No
Hydropower and irrigation – number of dams, percent of catchment regulated, percent of flow regulated	Image/GIS analysis	Good satellite imagery showing all dams constructed before 2016	Partially, need flow data
Rates of deforestation	Image/GIS analysis, scientific literature	Global Forest Watch 2000 to present	Yes
Areas disturbed by mining activities	Image/GIS analysis, scientific literature	Good satellite imagery between 1988 and 2016, with numerous years already digitised	Yes

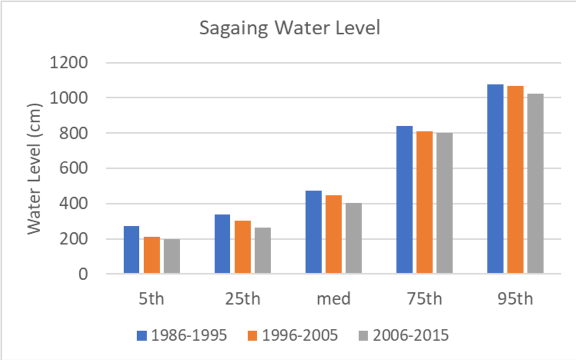
Indicator	Data Required	Preliminary Assessment of Data Availability and Quality	Suitable for Trend Analysis
Water clarity	TSS, turbidity, or suspended sediment concentrations	Insufficient data	No
Sediment grain-size	Sediment grain-size distribution	Insufficient data	No
Nutrient content of sediments	Nutrient content by grain-size	Insufficient data	No
Delta stability: Coastline evolution/mangrove loss	Scientific literature	Good analysis available from Webb et al., 2014	Partially
Delta stability: Groundwater extraction/delta subsidence	Groundwater extraction data	Unknown – need to liaise with SOBA 2	Partially
Delta stability: Sea level rise	Published sea level change predictions	Good	Predictions are ok, data for comparison are lacking

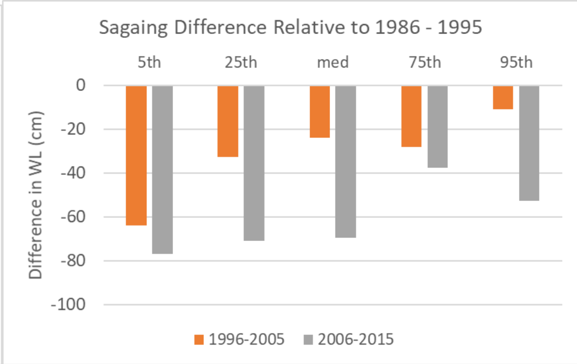
5.3 Trend Assessment

5.3.1 Hydrologic Changes

Hydrology is a major driver of sediment transport and geomorphic change. Evaluating whether flow rates or the timing of flow delivery have been altered will assist in understanding whether and how geomorphic processes might change. For example, a decrease in peak flows has the potential to reduce transport of coarse sediment, resulting in channel aggradation. Because the flow records have a low reliability, water level at the five gauging stations provided to the SOBA 3 Team by the DMH were analysed for changes over the period of record. It must be recognized that although the water level data are considered accuratethere is potential for the base level to change at the point of measurement which can alter the water level to water flow relationship. Discrepancies between flows at sites in the Ayeyarwady were briefly reviewed by the Activity 1 team, and although a variety of hypotheses were proposed, none were conclusively linked to the flow balance discrepancies.

A preliminary analysis of daily water level data was conducted using measurements from 1986 to 2015 at the gauging sites of Sagaing and Pyay. These sites were selected as Sagaing is in the middle Ayeyarwady, upstream of the Chindwin, and Pyay is in the lower river. These sites are located in areas with at least some degree of bedrock control of the river channel, so water level is less likely to be affected by channel alterations. The Sagaing cross-section was considered stable by the recent review (Walker, 2017). The cross-section at Pyay has been altered over time, but it is unknown how these changes affect the water level at the gauging site (IADS, 2017). The data were divided into three groups (1986 to 1995, 1996 to 2005, and 2006 to 2015), and the 5th, 25th, median, 75th, and 95th percentile flow levels for each data group were determined





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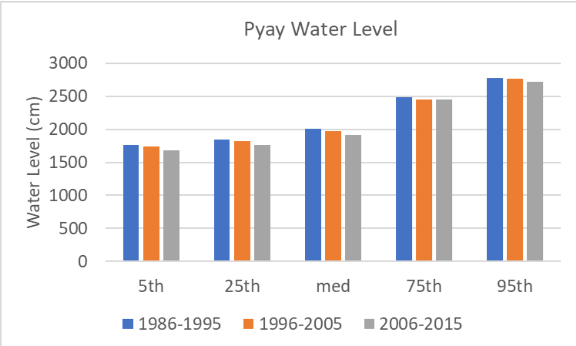


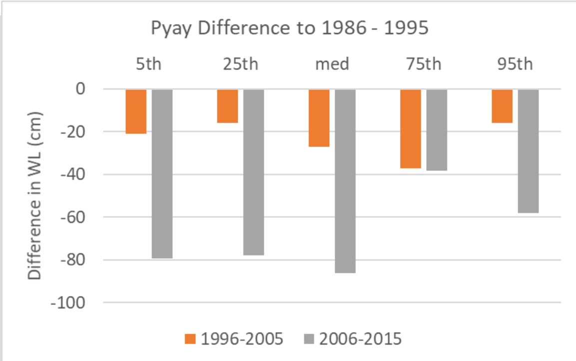
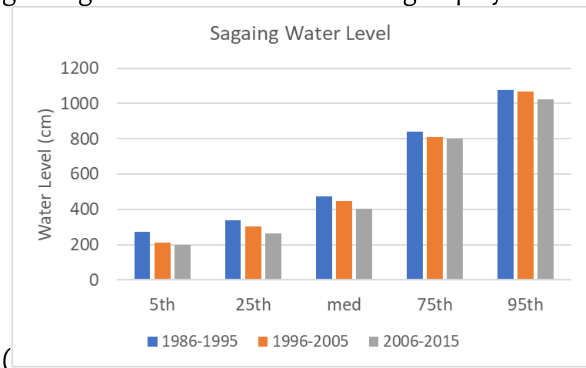
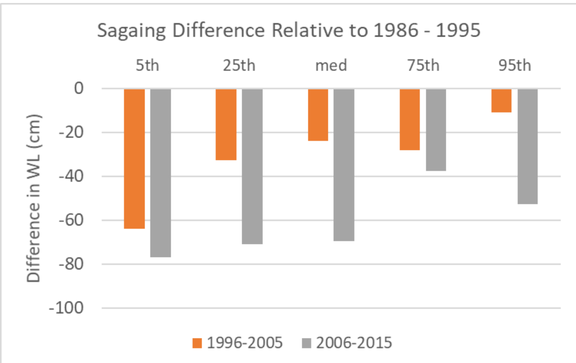


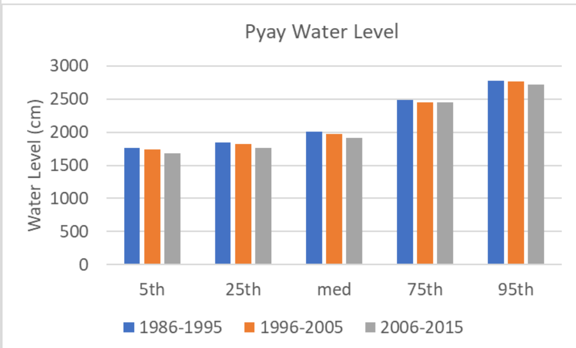
Figure 5.4). At both sites, the earliest dataset (1986 to 1995) had the highest values. The difference between the 1986 to 1995 results and each of the other groups (1996 to 2005 and 2006 to 2015) shows similar patterns at both sites, with the largest difference associated with the most recent data group. The results from both sites also show the smallest differences between the 75th percentile flow levels.

A more detailed analysis was completed by constructing histograms for each site and data group by 100 cm



water level bins. These results (





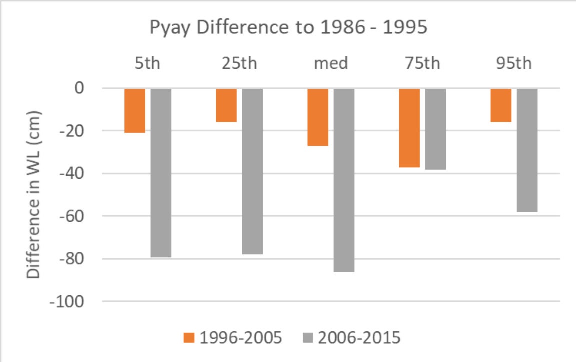


Figure 5.4) show the relationship is more complex than presented by the percentile groups. At both sites, there is a substantial increase in the frequency of low-flow levels (200 to 400 cm at Sagaing and 1700 to 1800 cm at Pyay) in the 2006 to 2015 data, as compared to the earlier time periods and a large decrease in the frequency of low to moderate flows (400 to 600 cm bins in Sagaing and 1900 to 2100 bins at Pyay). Both datasets also show reductions in the medium to high flows in the 1996 to 2005 period.

These changes could represent climatic shifts. Furuichi et al., (2009) concluded that flows in the Ayeyarwady had decreased over the past 100 years using flow results presumably derived from the same water level data as analysed here. If this is the case, then it is contrary to predicted climate change models that suggest the area will become wetter over time, rather than drier.

Other factors that could affect the water levels include changes to the bed level. If the bed elevation was reduced or increased, then water levels would be expected to show a uniform shift. Evidence against this being the primary driver includes the similarity in change between the two sites, and its nonuniform increase or decrease in level, which would be expected with a physical change in the cross-section.

Alterations associated with flow regulation, either by hydropower or irrigation dams could produce the observed changes, with an increase in low flows associated with discharges from impoundments during the dry season. The regulation of the Taping (Dapien), Shweli, Mali Creek, and Tabek in China, and in Myanmar the upstream of Sagaing, and the Myitnge, Zawgyi, and Mu downstream of Sagaing, may be altering the low-flow levels in the Ayeyarwady. At Sagaing, the potential for back water effects associated with increased dry season discharge from the large Yewy hydropower project in the Myitnge is also a possibility (e.g. seasonally higher discharges from the Myitnge are altering water levels recorded upstream at Sagaing).

The conclusions of Furuichi *et al.,* (2009), combined with the large number of regulated tributaries in the Ayeyarwady and this analysis, suggest that flows in the river are changing. Whether they have changed to an extent that is affecting the sediment transport, geomorphology, or ecology of the river is unknown, but additional detailed analysis of hydrologic data is warranted to better understand any potential flow changes. This is especially relevant when considering additional development within the catchment.

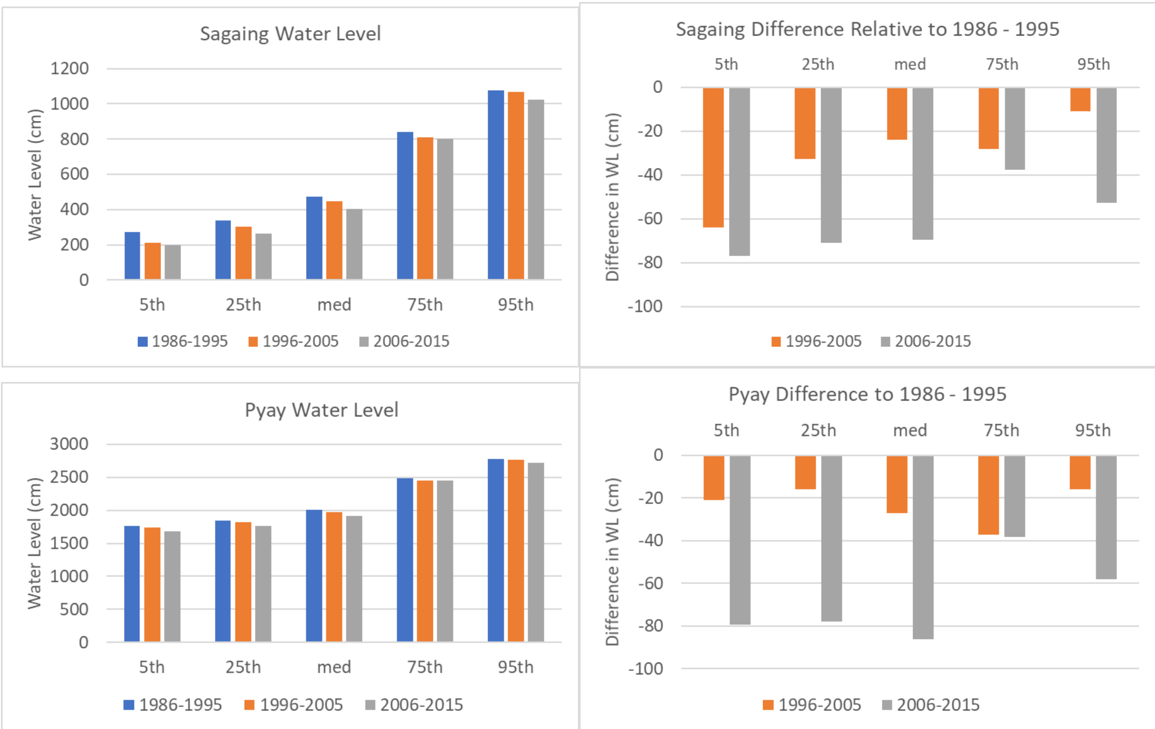


Figure 5.4 - Comparison of daily water levels at Sagaing and Pyay showing 5th, 25th median, 75th and 95th percentile flows for each site, and the differences between the values between the groups. (top) Sagaing (bottom) Pyay (Data from DMH)

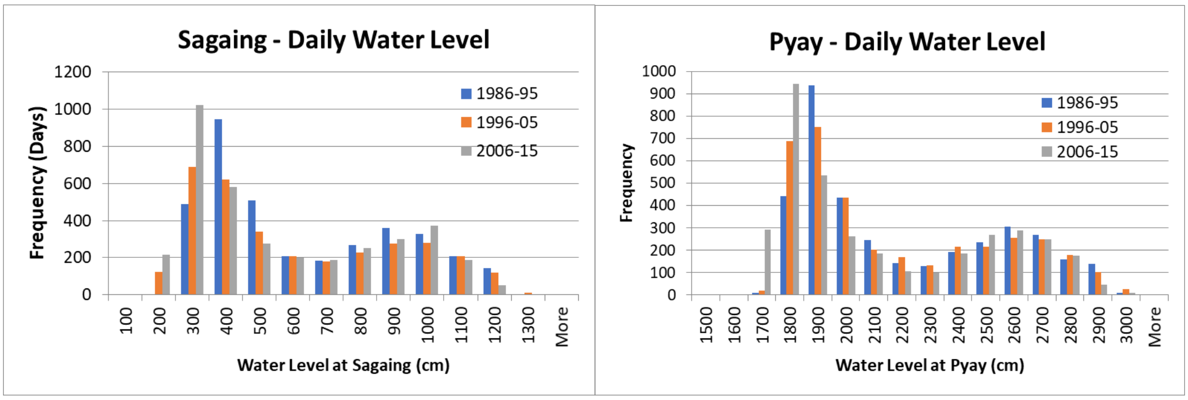


Figure 5.5 - Histograms of daily water level at Sagaing and Pyay by 100 cm water level 'bins'

Summary of trend analysis: There is evidence that low flows in the Ayeyarwady have changed over the period of 1986 to 2015, and these changes may be accompanied by reductions in medium to high flows. Future trends are likely to include additional flow changes associated with the implementation of additional hydropower developments, which are discussed below.

5.3.2 Channel migration

In principle, tracking the rate of channel migration could provide valuable information about whether the geomorphic attributes of the river are changing. In reality, channel migration occurs at a very local level, and natural rates include small annual incremental changes as well as major episodic events, so quantifying rates is difficult.

SOBA 3 has mapped channel changes between 1988 and 2016 based on satellite imagery at some of the sites monitored in April/May 2017 (see Section 0 and Annex 5). The results vary between locations, and present a snapshot of changes over the past two decades. It is recommended that this type of indicator monitoring be incorporated into a larger landscape based monitoring design and targeted to specific areas, based on the distribution of existing or planned land-based changes (e.g. some sites upstream and downstream of regulated or free-flowing tributaries, areas upstream and downstream of mining zones, areas upstream and downstream of intensive sand mining activities, etc.).

5.3.3 Flow regulation – hydropower

The disruption to flow and sediment transport caused by the physical obstruction of rivers has potential to alter river systems at both a local and large scale. There is no readily accessible list of all structures that alter water or sediment movement in the Ayeyarwady. The lack of this resource is an information gap and the compiling of such a database is recommended.

Information from an SEA of the Hydropower Sector in Myanmar (ICEM, 2017) was used to identify trends in the hydropower sector. The SEA has compiled a list of hydropower projects that are either operational or under construction as of 2017 and has identified projects that the Ministry of Electricity and Energy considers as in the planning stages for implementation by 2030. This list does not include small projects approved and administered at the local level, and includes only projects with identified commissioning dates.

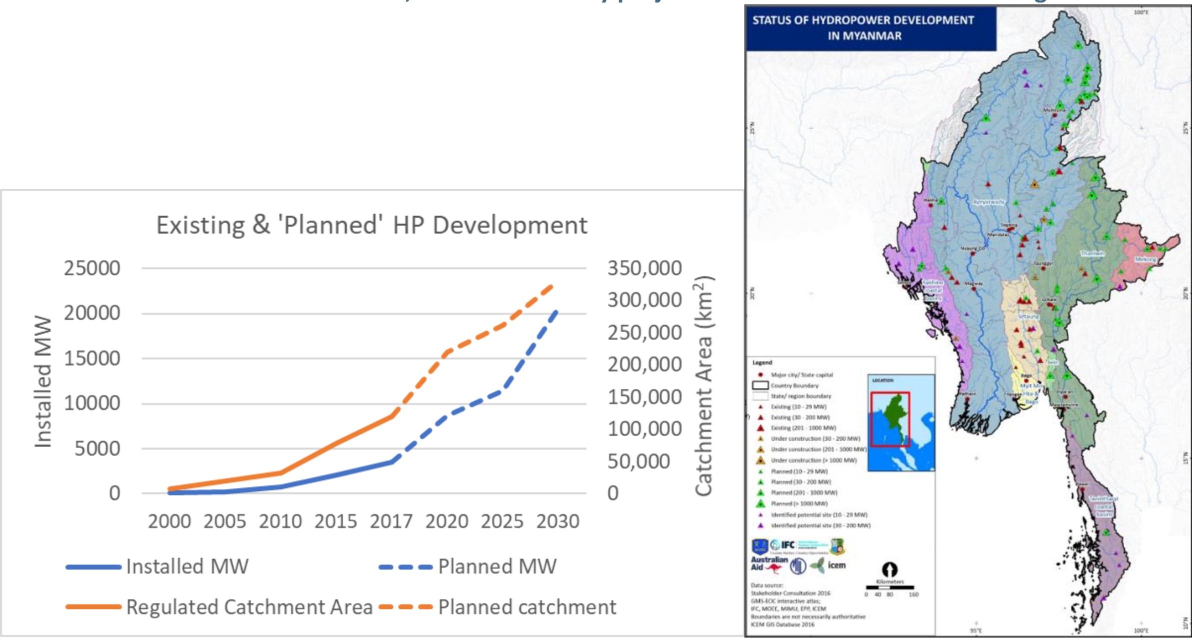


Figure 5.6 shows the levels of installed (and under construction) hydropower projects in the Ayeyarwady, with a trajectory showing hydropower development if all of the planned projects are implemented. An estimate of catchment area is also included, however it is an overestimate as some double counting has occurred due to the presence of multiple dams on the same waterway, with the area upstream of each dam included in the total. Regardless of this overestimate, the summary shows that at present up to ~25% of the 404,000 km^2 catchment area of the Ayeyarwady could be affected by dams. This is reasonable considering that the large tributaries have been developed (Shweli, Taping, Myitnge, Ma Gyi Chaung, Mali Creek, and Tampak). If all planned developments proceed, the regulated area and proportion of regulated flow in the Ayeyarwady would increase substantially.

An example of potential cumulative impacts is provided by Gupta et al., (2012) who collated the impact of mega dams (>100 m in height with reservoir volumes >1 km^3) on the sediment load in Asia. The results show a significant decrease in sediments at the mouths of the rivers as the number of mega dams increased. There are currently two mega dams commissioned in Myanmar (Shweli 3 and Yewya), and the dam heights associated with 20 of the planned projects exceed 100 m. Volumes are not available for all of the planned projects, but the >100 m dams also have projected storage volumes >1 km^3. Dams other than mega dams will also trap sediment and regulate flow.

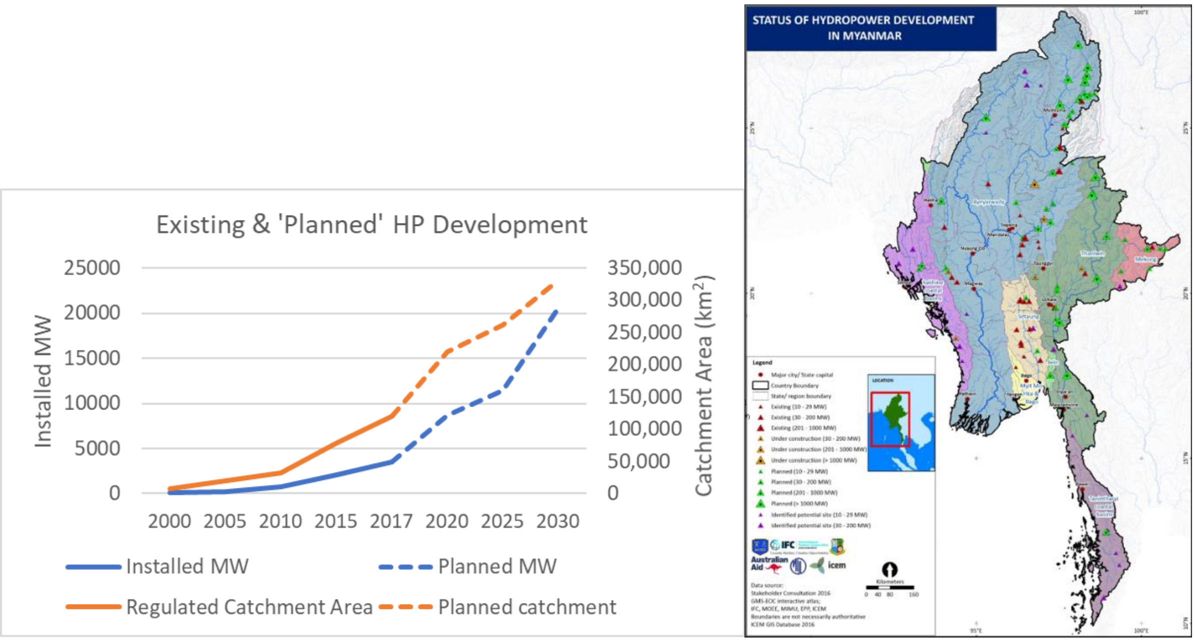


Figure 5.6 - Installed (existing and under construction) and 'Planned' hydropower projects through 2030 *based on ICEM (2017).*

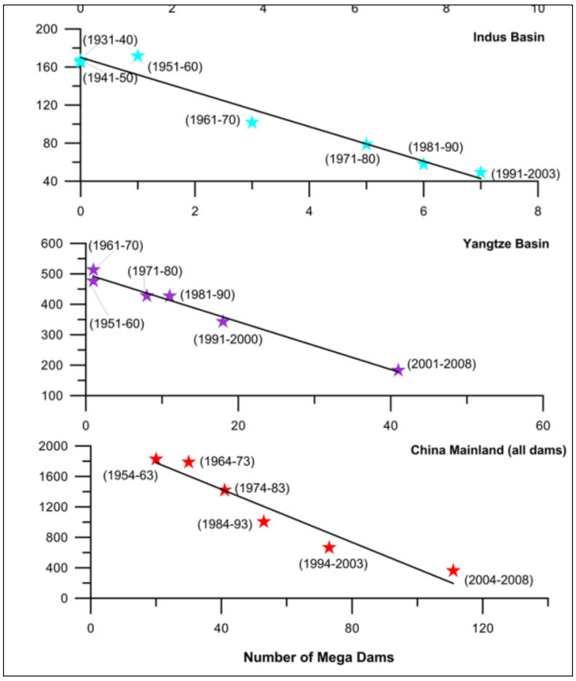


Figure 5.7 - Cumulative impact of Mega dams on rivers in Asia. Mega dams are defined as having dams >100 m in height and a reservoir volume > 1 km³. *(Source: Gupta et al., 2012)*

Summary of trend: At present there is a level of flow regulation in the Ayeyarwady that is likely affecting flow and sediment movement to some degree. This is consistent with the findings of the hydrologic analysis suggesting changes to the flow regime in the dry season. It is also consistent with the findings of recent delta investigations suggesting the resilience of the delta may be reducing, especially near the mouths of the distributaries. Myanmar is entering an era of increased hydropower development and the future trend shows a large increase in the regulation of flow and sediment trapping within the catchment. Many of the planned future developments include high dams and very large storages, increasing the capacity for flow alterations and sediment trapping. Collectively, these projects have the potential to substantially reduce sediment loads, alter flows, and reduce the connectivity of the Ayeyarwady through increased fragmentation.

5.3.4 Irrigation

The lower Ayeyarwady has undergone substantial irrigation-related water development (

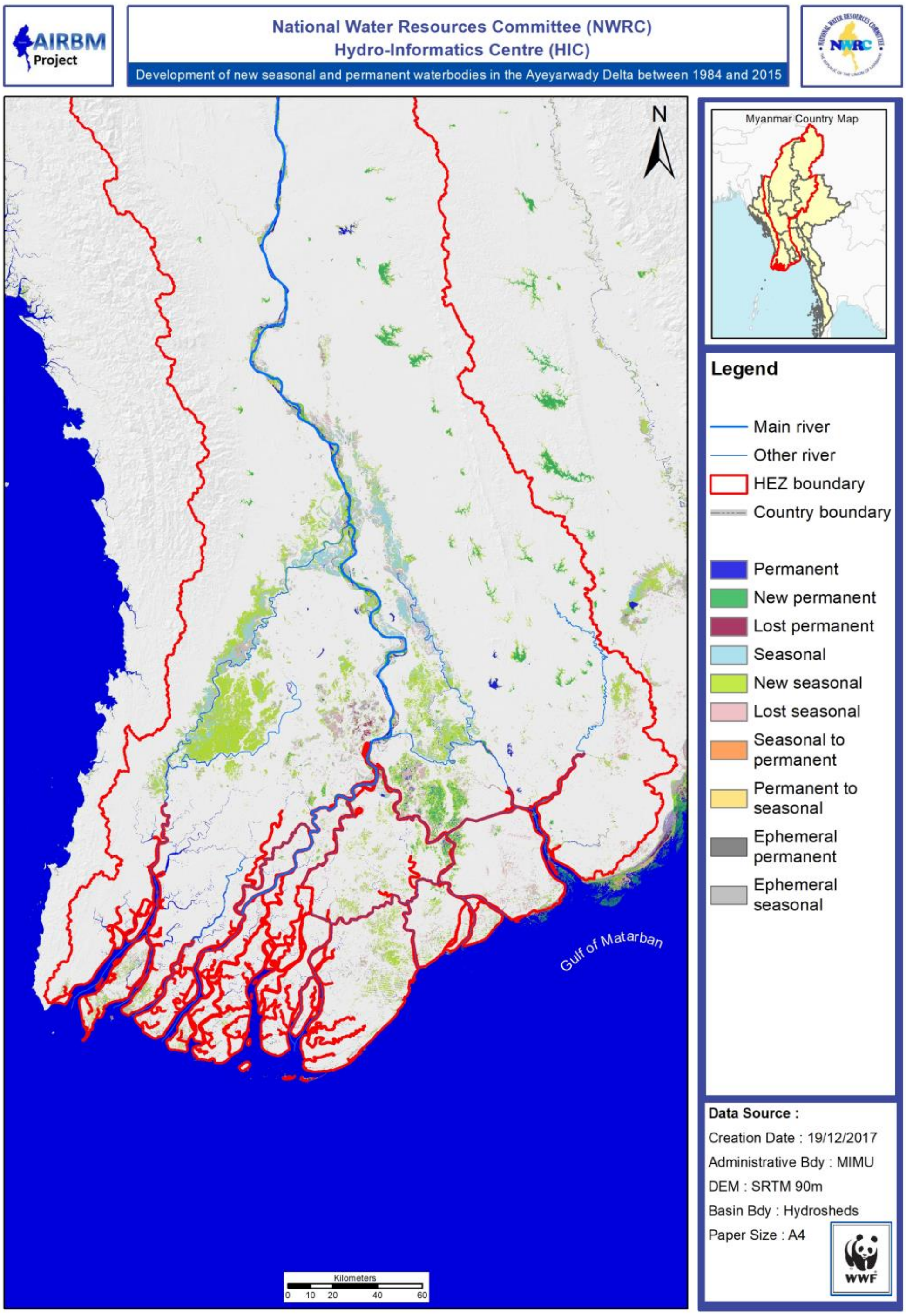


Figure 5.8, Global Surface Water), with both permanent and non-permanent water bodies developed between 1984 and 2015. The analysis suggests that most development has occurred on the floodplains and along the distributaries of the river in the delta. These types of water resource development projects have the potential to alter the timing and delivery of flow and sediment to the delta and the delta front, where the timing of sediment introduction, as well as the magnitude, is important for maintaining the stability of the delta.

The extraction of groundwater for irrigation is another activity that can alter the hydrology of the river and delta. Groundwater extraction has been linked with ground subsidence of potentially up to 9 centimetres per year (cm yr^{-1}) in the Yangon area (Van der Horst, 2017), but no information is available for the Ayeyarwady floodplains, delta or Dry Zone. Changes to the hydrology of the river and delta can also affect the extent of salt water intrusion, and thus the usability and productivity of large areas.

Summary of trend: The existing level of irrigation development likely has an impact on flow and sediment regimes within tributaries, and collectively, may be altering the flow in the Ayeyarwady, similarly to hydropower but more localised in the Dry Zone and lower river system. There is no long-term plan available for future irrigation developments as there is for hydropower, but the growing population and drive to boost the productivity of the agricultural regions in the Ayeyarwady will likely increase irrigation pressures in the future. These developments, and their potential influences on the system need to be considered on a cumulative basis, and in conjunction with flow and sediment changes associated with hydropower development. There is a high risk that the flow, sediment delivery and connectivity of the Ayeyarwady could be irrevocably altered due to development and implementation of individual projects without consideration of the overall system.

This trend is similar to that of hydropower. At present there is a level of flow regulation in the Ayeyarwady that is likely affecting flow and sediment movement to some degree. This is consistent with the findings of the hydrologic analysis suggesting changes to the flow regime in the dry season. It is also consistent with the findings of recent delta investigations suggesting the resilience of the delta may be decreasing, especially near the mouths of the distributaries. The future projected trend is a large increase in the development of hydropower, which would increase the regulation and sediment trapping within the catchment. The potential for future irrigation has not been able to be quantified by the SOBA 3 Team.

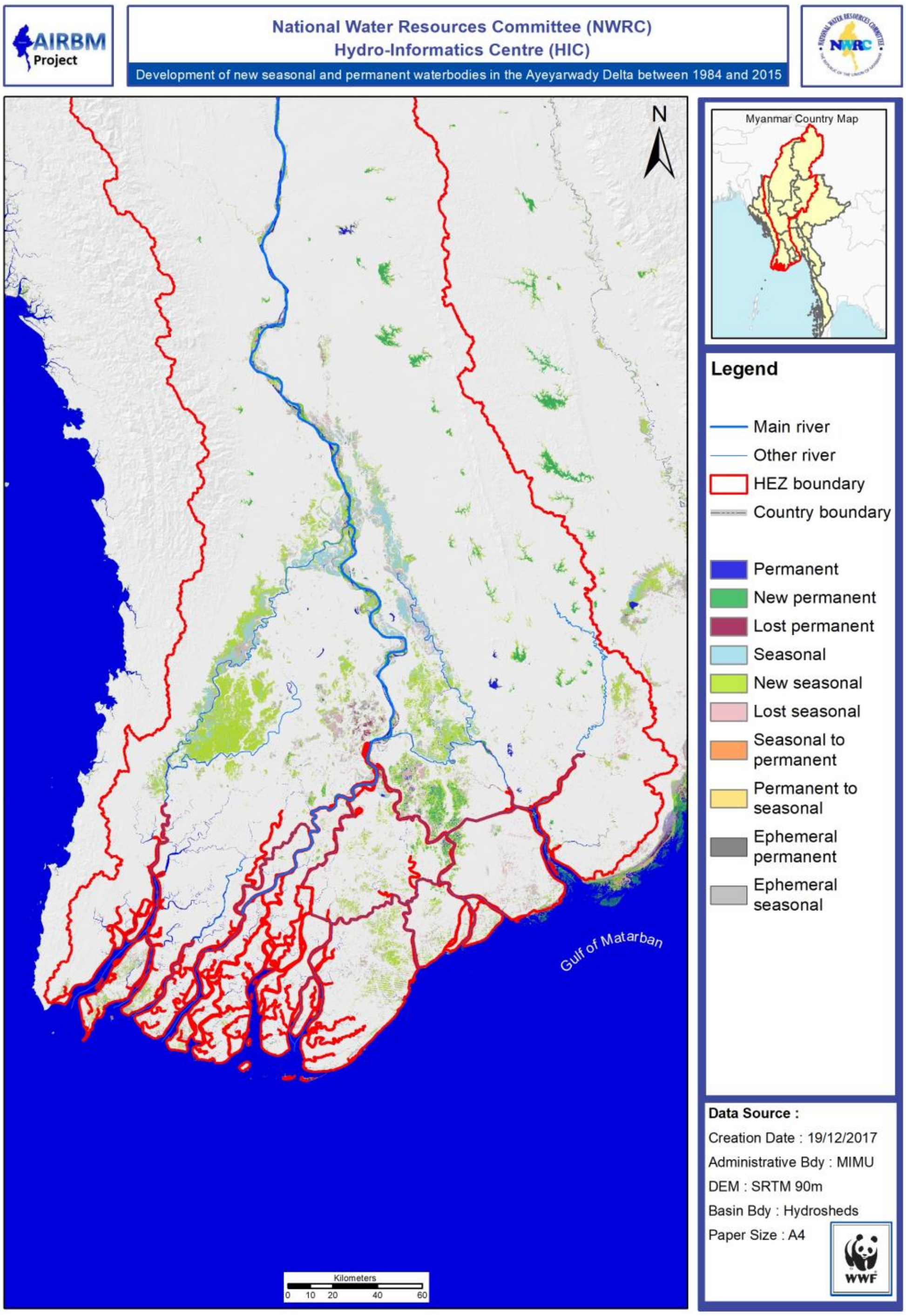
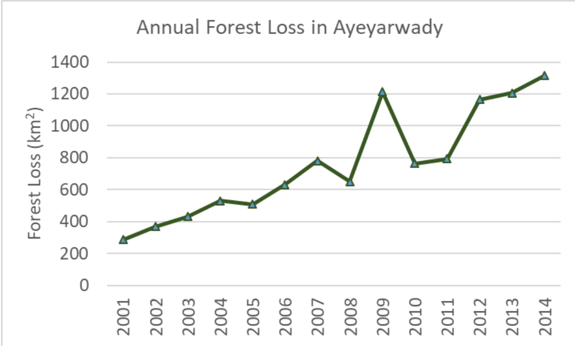


Figure 5.8 - Development of 'new' seasonal (light green) and permanent (dark green) water bodies in the lower Ayeyarwady between 1984 and 2015. *(From Global Surface Water Explorer https://global-surface-water.appspot.com/)*

5.3.5 Land use changes: deforestation

Deforestation can affect sediment input to rivers and the volume and pattern of water runoff (see Section 3 for a more detailed discussion). As noted in Section 3, the annual rate of forest loss in the Ayeyarwady is



increasing, resulting in a large cumulative loss (

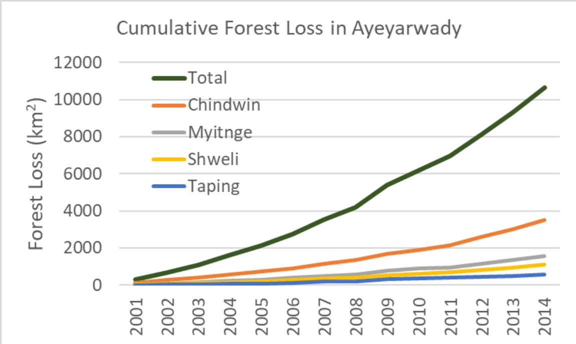


Figure 5.9). The reduction is spread amongst the tributaries, with the larger catchments (Chindwin, Myitnge, Shweli, and Taping) recording the largest areas of deforestation. Deforestation maps suggest that clearing may be a transboundary issue, with high concentrations of tree cover loss occurring near both the eastern and western national borders in northern Myanmar.

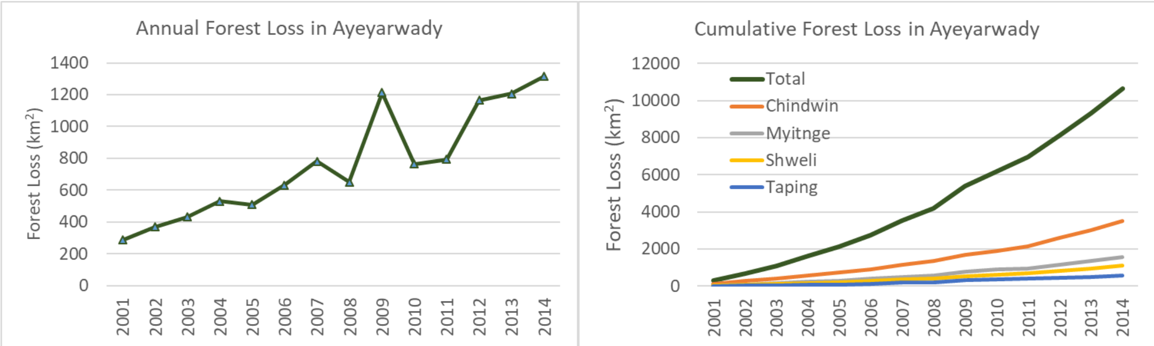


Figure 5.9 - (Left) Annual rate of forest loss in the Ayeyarwady basin (right) Cumulative area of forest loss in the Ayeyarwady, showing contributions from four major tributaries *(Data from Hansen et al., 2013)*

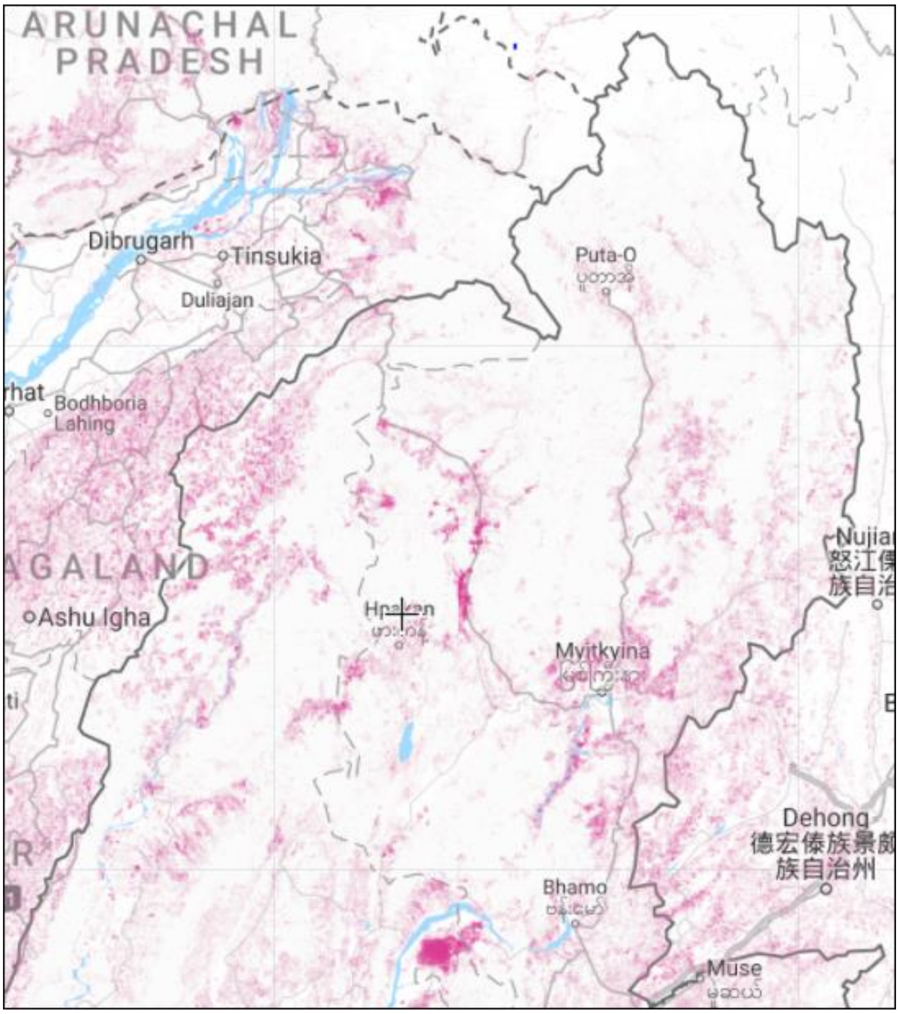


Figure 5.10 - Map of northern Myanmar showing areas of deforestation between 2001 and 2015.Pink areas indicate areas of tree loss (>30% canopy cover) and are more intense near the eastern border with China and the western border with India. (: http://www.globalforestwatch.org)

Summary of trend: Rates of deforestation have risen over the past decade in the Ayeyarwady, and unless land management policies change, deforestation is likely to increase into the future. As the more easily accessible forested areas are reduced, there is an increased risk that steeper areas will be cleared, which could have large detrimental impacts on rivers due to the steeper slopes being more prone to erosion and mass-failure. A growing trend in deforestation will likely increase the sediment input to rivers in some areas.

5.3.6 *Land use changes: Terrestrial mining*

A discussion of the potential impacts of terrestrial mining on river systems was presented in Section 3.2. In recent years the disturbed areas associated with mining have increased, with an especially large increase occurring between 2010 and 2016 in the Ayeyarwady River (

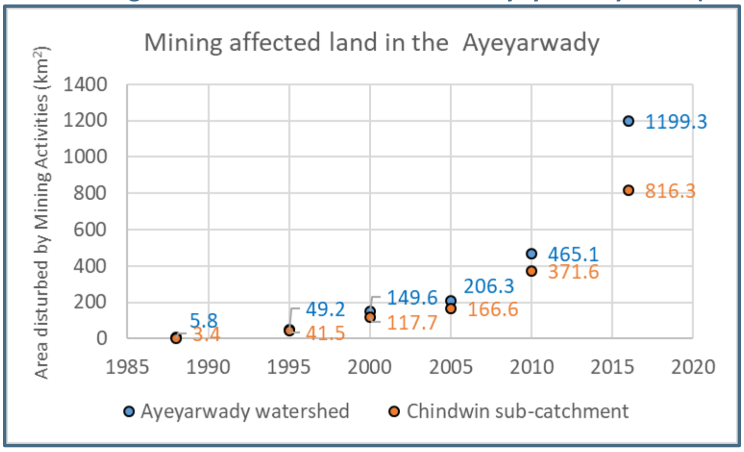


Figure 5.11). Field observations made by the SOBA 3 Team included abundant small mining waste piles near the bank of the river in the upper Ayeyarwady, and increased sediment input into the Ayeyarwady in the area of the Sagaing fault, attributable to mining activities.

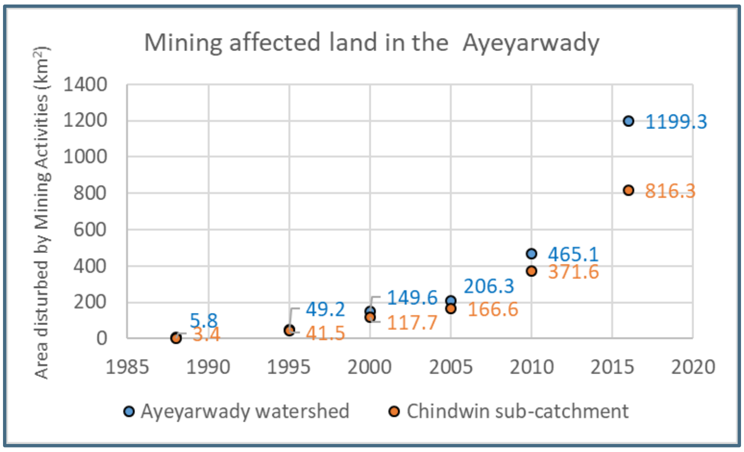


Figure 5.11 - Mining affected land in the Ayeyarwady 1986 to 2020

Summary of trend: The areas disturbed by mining in the Ayeyarwady have increased at a high rate over the past decade, and are likely to continue to increase in the future. In the absence of increased land management and regulations regarding the storage of mining waste, mining activities are likely to increase sediment inputs to the river in localized areas, and have the potential to affect the entire river of the Ayeyarwady.

5.3.7 *Sand and gravel mining from the river*

The extraction of sediment impacts the geomorphology and sediment transport of rivers in a number of ways. Locally, the extraction of material can deepen channels that in turn can destabilize the local riverbanks as the channel adjusts to the deeper conditions. The local extraction of material can alter the morphology of the bed, leading to an alteration of local river currents. Deeper and steeper channels can also increase the velocity of river flows which exacerbates erosion. Once the morphology of a channel is changed in one location, these changes can propagate downstream, as the river reaches adjust to the change in river slope, flow velocities, and sediment arriving from upstream.

Typically, coarse sand and gravel is targeted for extraction as these are the most desirable construction materials. These sediment sizes tend to be transported as bedload, and in the Ayeyarwady make up a small proportion of the overall sediment load based on the grain-size distribution of over 300 bank and bed samples collected by the SOBA 3 Team. The disproportionate removal of this coarse material will alter the characteristics of the sediment load moving downstream, potentially affecting the stability of the downstream channel, and increasing the risk of channel incision. A reduction in the delivery of material to the delta channels and delta front can promote delta instability and subsidence.

Summary of trend: There is little information available regarding sand and gravel extraction from the Ayeyarwady. The SOBA 3 survey (Section 3.4) provides a snapshot that can be used to develop a more complete surveying and monitoring system. However, given the level of development in Myanmar, and the large volumes of sand and gravel required for construction, road building, and dam building, it is suggested that the extraction of material from the river and its tributaries is increasing, and the future trend will be the extraction of even greater volumes.

5.3.8 Coastline evolution and mangrove loss

Mangroves provide stability to the delta front and protect it from wave, wind, and storm surge erosion. A decrease in the forest cover of the delta has been documented since 1978 (Webb et al., 2014). The same study projected that deforestation was likely to continue due to the importance of agriculture to the growing Myanmar economy, the introduction of new investors, insufficient land tenure agreements, and governance issues. The work of Edward et al., (2017) suggests the resilience of the delta may be declining, which could be linked to deforestation, as well as changes to sediment delivery to the delta, and hydrologic changes.

Summary of trend: The Ayeyarwady coastline is under stress due to land use pressures. The proximity of the delta to the most populous area of the country will likely increase these pressures in the future, without the implementation of sound land and water management policies.

5.3.9 Climate change and sea level rise

Climate change is a risk to the Ayeyarwady catchment and delta because it has the potential to substantially exacerbate impacts associated with other activities, such as increased erosion associated with deforestation (including mangroves), or decreased flows in the dry season, associated with higher temperatures and increased evaporation. Recent climate risk profiles from US Aid (2017) list the following projections of change:

- an increase in 0.5° to 5.5°C increase in temperature by 2100;
- reduced duration and increased variability of the southwest monsoon;
- increased frequency and intensity of extreme weather events;
- increases in sea level of 0.2 to 0.6 m by 2100; and
- increases in rainfall variability during the wettest months (May to October), with rainfall ranges predicted to vary from a decrease of 45 mm $month^{-1}$ to an increase of up to 200 mm $month^{-1}$ compared to the present patterns.

Summary of trend: The above predictions identify the expected future trends in climate change. To be useful as a management indicator, good climate data and an understanding of how climate change will interact with other catchment changes and geomorphic processes are required. The management of climate change is best achieved through maintaining the resilience of river and coastal systems. This resilience is linked to the inherent variability of river systems, the maintenance of key flow and sediment pathways, and the protection of natural assets, such as riparian and coastal vegetation, that provide the first line of defence against extreme events.

6. INFORMATION GAPS - SEDIMENT MONITORING

6.1 Introduction

The SOBA 3 Terms of Reference includes the requirement to identify and characterise major data gaps and develop an initial design for a multi-year sediment monitoring program to be implemented during the AIRBM project. This section of the SOBA 3 report provides a discussion regarding the need for comprehensive and integrated monitoring, existing sediment monitoring data and availability, data gaps identified during the SOBA 3 activities, the requirements for collecting high-quality data, and a tentative pathway forward for development and implementation of a program to achieve these requirements.

Sediment monitoring in the SOBA 3 Terms of Reference is not defined, but is considered to include the measurement of sediment being actively transported through the river as either suspended material or bedload, and the overall changes to river channels that are required to provide accurate measurements of sediment transport, and provide an understanding of the fluvial geomorphic processes necessary for underpinning long-term management decisions and actions. Understanding how much sediment moves through a river can provide a sediment budget and information about the timing and pattern of sediment transport, which is critical for understanding short-term changes and links between sediment movement and ecological processes. This information becomes even more valuable and usable if there is also an understanding of the large-scale, long-term changes and trends that are occurring within the river. Obtaining an understanding of trends on timescales of years to decades provides a context within which to interpret the annual sediment transport results, which have high annual variability, and in the case of the Ayeyarwady, are likely to be controlled by multi-year processes (e.g. large sediment influxes some years may affect sediment transport for multiple years following the event).

6.2 Why Monitor Sediments?

Understanding sediment transport and geomorphic processes is required to understand and potentially manage the following processes:

- Channel stability and the protection of infrastructure — The migration of river channels within the Ayeyarwady is a long-recognised process, and one that affects many of the uses of the river. Bank erosion is an ongoing issue for communities located along the river, and understanding sediment transport and long-term trends will assist in identifying areas where there would be a high risk of erosion to potential developments. Channel stability can be managed through controlling activities that can promote bank instability, such as sand and gravel mining.

Figure 6.1 - Photo of pagoda collapsing into the Ayeyarwady River due to bank erosion. *The Thiri Yadana Pyilone Chantha Pagoda collapsed on July 20, 2017 during high flow in the Magway region. The temple was constructed in 2009 when it was' far away from the river' according to residents (http://www.straitstimes.com/asia/se-asia/floodwaters-swallow-myanmar-pagoda)*

- Navigation — The 'Road to Mandalay' is as active a highway as it was a century ago, and continued development and economic growth is linked to low-cost dependable transport. Understanding sediment transport, channel migration rates, and likely future directions can assist in the long-term design and maintenance of sustainable navigation channels. Understanding where infrastructure will not yield long-term improvements to navigation is as important as identifying areas where interventions may improve navigation.

Figure 6.2 - Photo of grounded barge in Ayeyarwady in January 2017

- The Ayeyarwady Delta is home to approximately 15 million people (Brakenridge et al., 2017), and is a highly productive agricultural area. All deltas are dependent on the continued delivery of sediment from the river catchment, and the Ayeyarwady Delta has been identified as one of the few large Asian deltas that continues to grow, with net growth recorded over the period of 1974 to 2015 (Anthony et al., 2017a). Importantly, this period included the robust recovery of the delta following tropical cyclone Nargis in 2008, when up to 1 km of the delta front was eroded. Within four months, much of the delta front was restored to its previous extent. However, the most recent investigations have found that this growth trend is changing, with about half of the delta showing erosional trends, especially near the mouths of the distributaries, which is the transfer zone for material between the river and the sea (Anthony et al., 2017a). Understanding sediment transport in the Ayeyarwady is critical for managing and maintainning a robust delta that will continue to support the people and agriculture of Myanmar, and provide protection from inevitable future cyclones.

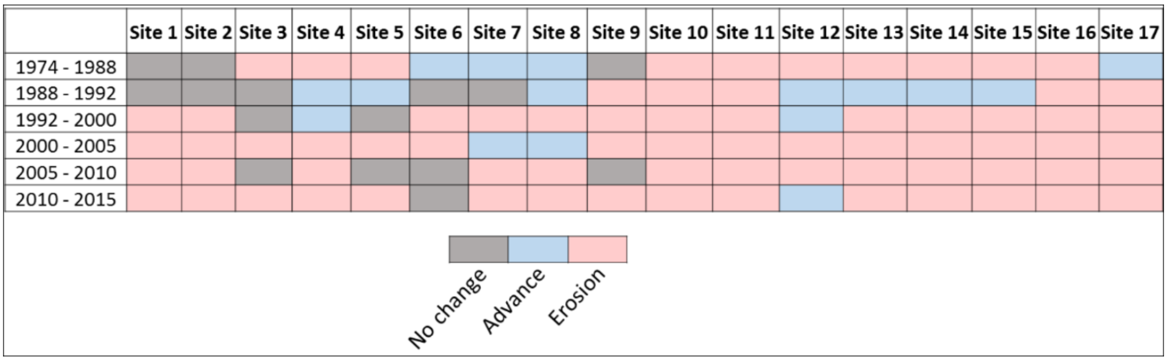


Figure 6.3 - Results of a vulnerability assessment of the delta showing trends in erosion and advance. *Sites 10 through 17 are located at the mouths of the distributaries of the Ayeyarwady with the other sites located towards the east of the delta front* (Anthony et al., 2017a)

- Ecological systems and habitat distribution and quality — The productive fishery and other aquatic ecosystems of the Ayeyarwady underpin an important source of food for Myanmar, and support the biodiversity of the country. These systems are linked to the distribution and quality of ecological habitats, which are largely governed by the transport, delivery, and removal of sediments over a range of timescales. Examples of these processes include the delivery of nutrients to floodplains via the deposition of fine sediment during the flood peaks, or the removal of fine silts and clays from pebble or cobble habitats on a seasonal basis, making them suitable for fish spawning. An understanding of sediment transport is required to manage and protect the physical systems which support these important ecosystems.

- Nutrient transport — Nutrients are a fertiliser for natural vegetation and agriculture, and the first step in the aquatic food chain, which is key for fisheries. Nutrient loads are closely linked to sediment loads, as a large percentage of nutrients are typically either attached to sediments and transported, or occur as organic particulates contributing to the total sediment load. The sustained transport and delivery of nutrients onto floodplains and other ecological niches is necessary for the continued agricultural productivity of floodplains and maintenance of fisheries and other ecological food webs. Development activities, such as hydropower or irrigation development, can modify sediment and nutrient transport through the trapping of material, and alteration of flow regimes that change the downstream dispersal patterns. Understanding how nutrients are transported by the Ayeyarwady, (e.g. with which sediment grain-sizes, as dissolved or particulate nutrients, linkages with the seasonal timing of flows, etc.) will allow more accurate predictions to be made, with respect to impacts associated with development, and importantly, assist with the identification of appropriate mitigation measures.

- Monitoring landscape changes — Myanmar is situated in one of the Earth's unique tectonic settings. There is great interest and investment of scientific effort in understanding the complexities of the tectonically active country, and how these complexities are reflected in landscape attributes (e.g. Wang et al., 2014). Sediments provide insights into past geologic conditions and can help elucidate the processes that have given rise to the present landscape, such as Litch et al., (2014) using sediment composition to track changes in the source of material in the Ayeyarwady over time. Providing accurate sediment transport measurements will assist in the scientific understanding of the landscape and its history, and thus allow a better predictive capacity with respect to its future.

6.3 Existing Sediment Monitoring and Available Data

SOBA 3 has been provided with historic water level, discharge, and suspended sediment time series by the PMU that were sourced from DMH. Discussions with DMH personnel during SOBA 3 found that the agency does monitor sediments in the Ayeyarwady, but the data are not included in the historical information provided.

Discussions with DMH personnel have provided a brief overview of how suspended sediment measurements are collected. The method is based on a weighted bottle with a plug in the top being lowered into the water column. Once at the desired depth, the plug is removed and the bottle is retrieved. As discussed in Section 6.6.2, this approach will capture the wash load but will not accurately collect large silt or sand sized material, which constitutes the material most important to understand, yet most difficult to accurately sample. It is recognised that the sampling protocol implemented by DMH is the best technique available to the agency, and that limitations of the method are linked to the lack of suitable equipment and resources.

6.3.1 *Available sediment data*

A review of the available sediment data for the Ayeyarwady was presented in Section 4 (Sediment Transport and Characteristics – Review of existing data). The review concludes that the data is not suitable for the development of sediment budgets for a variety of reasons, including:

- Recognized inaccuracies in the underlying hydrologic flow data;
- Lack of revision of the sediment-flow relationship over time, ideally annually; and
- No access to original sediment monitoring dataset to provide insights into when and how the flow-sediment relationships were derived.

These identified shortcomings are not a criticism or a reflection on the people or agencies working in the fields of hydrology and sediment transport in Myanmar, the groups that have been instructed to interpret these data, or the existing systems with respect to sediment monitoring or data management. Sediment monitoring is difficult, expensive, and time consuming, and thus can often become a low priority compared to other national needs, especially in a developing country facing innumerable challenges, such as Myanmar. Recognising and discussing the shortcomings is the first positive step towards addressing the issues to arrive at an improved sediment monitoring system in an integrated and cost-effective manner.

6.4 Sediment Data Gaps

The conclusion from the review of existing suspended sediment data is that it is not reliable and should not be used as the basis for understanding the Ayeyarwady or underpinning management decisions. Sediment information gaps identified during SOBA 3 include:

- Accessible repeat surveyed river cross-sections or long-sections that capture seasonal or annual changes in the river;
- Ongoing suspended sediment monitoring results using techniques that accurately quantify the movement of material through the river, at timescales appropriate for the seasonal flow regime;
- Grain-size information about the sediment being carried in suspension; and
- Bedload and bed material information. Bedload moves episodically through the system and likely accounts for a relatively low percentage of the overall sediment load in the Ayeyarwady. However, the bedload component is most important with respect to channel stability as it is dominated by the coarser materials that are exposed during periods of low water. Quantifying as much as practicable the magnitude and grain-size characteristics of bedload is required to understands how channels are likely to respond in the future to existing or altered flow regimes. The SOBA 3 field survey has provided a high-level first survey that can be used as a reference for future work regarding bed materials. However, greater sampling density and sampling during both the dry and wet seasons is required to provide a true picture of the bed materials in the system.

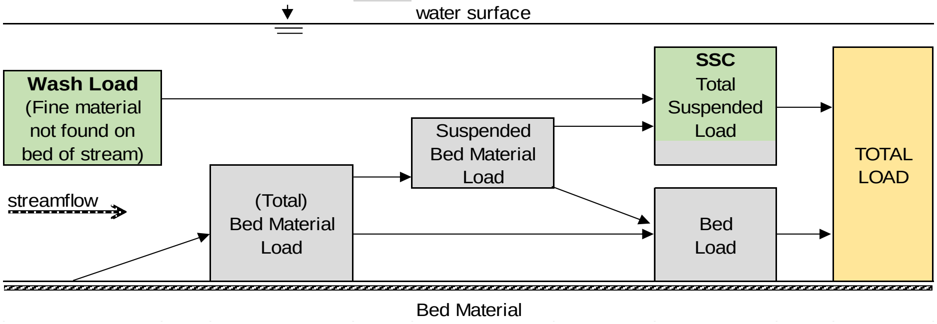
6.5 Components of Proposed Sediment Monitoring Strategy

Different agencies or groups in Myanmar may need to monitor sediments for different purposes. For example, DWIR may require sediment transport information in localised areas of the river for the development of sediment models, whereas DMH has the responsibility to provide ongoing routine monitoring at fixed sites, over periods of years to decades, for the establishment of long-term time series. Similarly, specific developments, such as hydropower, will require sediment monitoring in tributaries and in areas of the Ayeyarwady upstream and downstream of tributary confluences to evaluate potential impacts and develop appropriate mitigation measures.

A sediment monitoring system needs to meet these different needs, and can be easily adopted by all groups investigating or monitoring sediments. Uniformity of monitoring techniques and laboratory analyses provides the benefit that datasets are congruent and can be integrated. The characteristics of such a system include the following:

- Accurate discharge measurements — Accurate discharge measurements are required to obtain accurate sediment transport measurements. Discharge measurements need to be completed at the same time and place that sediment monitoring occurs. Considerable work and investment is being made in discharge measurements, and sediment monitoring should be integrated into the upgrading of the gauging system.

Accurate suspended sediment monitoring technique — Total sediment transport in a river is comprised of different components as shown in



- Figure 6.4. Sediment is not transported uniformly through the water column, or across a river cross-section with different grain-sizes transported under different flow velocities (

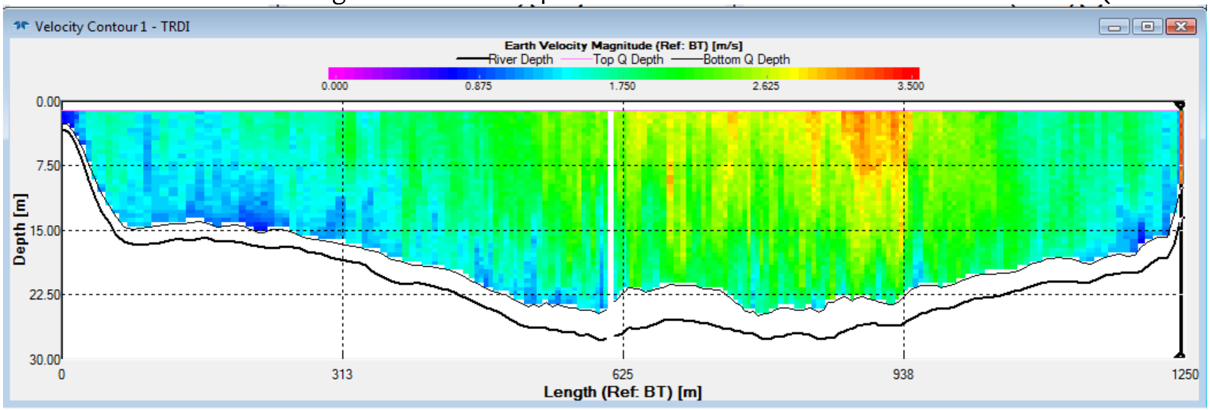


Figure 6.5). The concentration of very fine material (clays and fine-silts) in the wash load is generally uniform in a river, as it is maintained in suspension at all river flow velocities. The transport of coarser material (coarser silt, sands, and gravels) is dependent on the flow velocity of the river, with sediment concentration varying with depth in the water column, and across the section of the river. The monitoring technique adopted for suspended sediment sampling must be able to accurately collect sediment in the proportion that it is transported in the river, both with respect to depth and across the cross-section of the river.

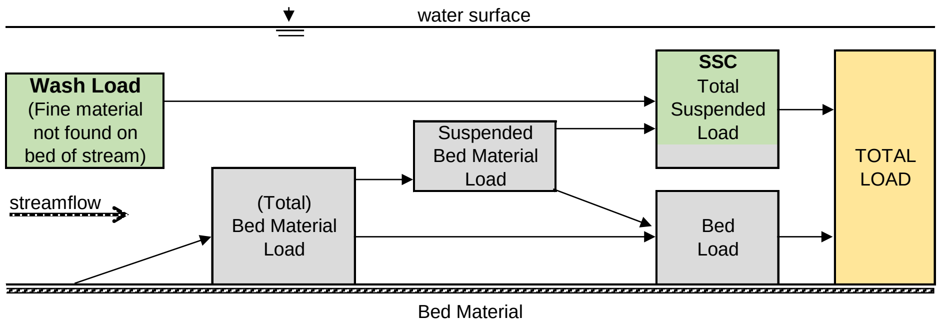


Figure 6.4 - Components of the total sediment load transported by rivers
(Poplawski et al., 1989)

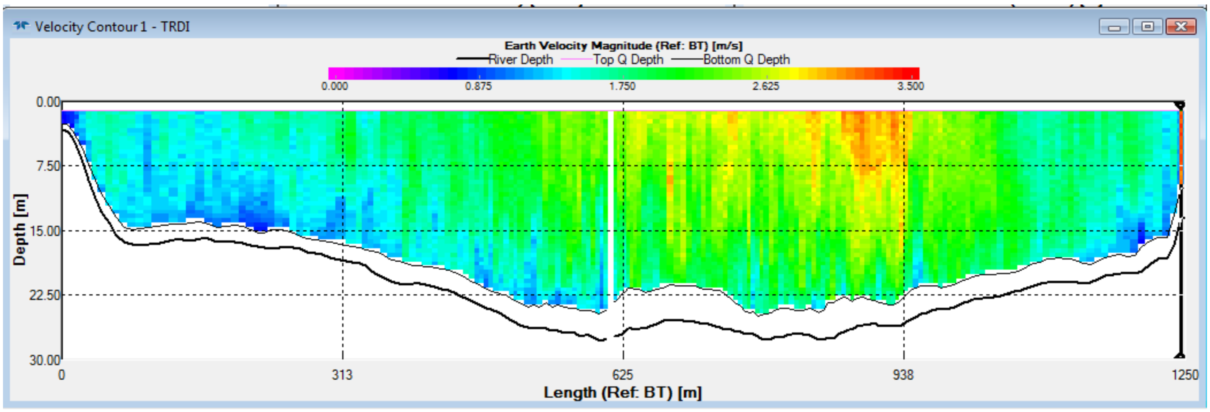


Figure 6.5 – Acoustic Doppler Current Profiler (ADCP) profile of river cross-section showing velocity differences across the river. *Flow velocities in a river vary with depth and distance across the channel. Colours indicate water velocity in metres per second (m s^{-1}) with blue showing areas with velocities of <1 m s^{-1} and red showing areas with velocities >3m s^{-1}*

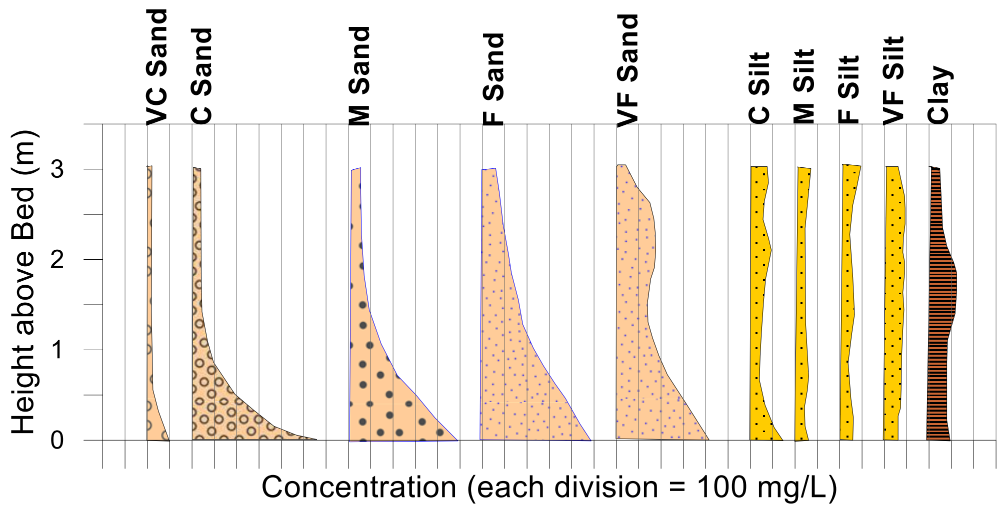


Figure 6.6 - Concentration of different sediment grain-sizes fractions by depth. *Each square represents 100 mg l^{-1} with the depth shown in feet along the y-axis. Sand transport is concentrated near the bottom of the water column. (*Based on FIP Reports, 1963)

- Water quality monitoring is completed at the same time as suspended sediment monitoring, such that an accurate determination of water quality parameters that are associated with sediments can be gained.
- The bedload monitoring technique can quantify the volume and grain-size of material moving as bedload.
- The bed material sampling collects grab samples of the material on the bed of the river.
- A data management system stores all flow, sediment, and water quality data. The system should provide a platform for the QA/QC of the data, and be able to store meta-data summarising the methodologies used for collection and analysis of each sample type, as well as other relevant information (e.g. when rating curves are updated, who collected the data, why the data was collected, etc.). The data management system should provide a secure long-term repository for all sediment and flow data, and provide easy retrieval of results.
- Appropriate cross-agency ongoing capacity building ensures consistency of sediment monitoring collection methods and data analysis. Important within this is ongoing training and capacity building to provide redundancy within and between agencies, and ensure the continued delivery of the monitoring program over time, with no loss of capacity as people leave the agency.

6.6 Strategy for Long-term Monitoring

6.6.1 Development of Remote Sensing Techniques for Monitoring Sediment Transport

The over-arching aim of monitoring is to collect consistent, high-quality information in a safe and cost-effective manner. Safety is very important, as it is inherently dangerous to be in a boat on a river under conditions of high flow. Deploying monitoring instruments from a boat under these conditions further increases risks, due to the potential of equipment becoming snagged on large logs or other items on the bed of the river or moving downstream, and overturning the boat or injuring people onboard as wires snap.

Monitoring techniques that rely on remote sensing, such as ADCP, rather than deployment of a physical instrument down the water column, are safer and can provide more information than point source measurements. One of the long-term aims of the monitoring strategy should be to identify and develop techniques that can be easily and safely deployed while providing high-quality data.

Developing ADCP-based techniques to monitoring sediment discharge as well as flow discharge is recommended. The instruments are used to monitor river flow in the Ayeyarwady, and it is strongly recommended that the implementation of a sediment monitoring strategy be established with the ongoing roll out and implementation of ADCP for flow gauging. However, because these instruments require extensive calibration before the digital data can be interpreted with respect to sediment concentrations, suspended and bedload sediment sampling needs to be completed in parallel with the ADCP measurements. The physical monitoring of sediments will provide a rapid improvement in the understanding of sediment transport in the river, as well as provide the basis for long-term calibration of ADCP results. Ongoing physical monitoring will also be required to check and update calibrations.

6.6.2 Suspended sediment monitoring

ADCPs measure water velocity by evaluating the echo of sound waves off particulates in the water column and the bed of the river. The strength of the received signal is proportional to the quantity of suspended matter in the water column, and there is potential to measure the suspended sediment content of the river by interpreting the signal strength. However, the relationship between signal strength and suspended sediment concentration is highly dependent on the characteristics of the sediment in transport, with grain-size and shape affecting the results. The relationship can also change as flow rates and the types and quantities of sediment change. Therefore, it is necessary to calibrate the relationship between sediment concentration and ADCP signal strength at each monitoring site where it is intended to be used, and under a range of flow conditions. In the Ayeyarwady, this would require two or more years of the physical sampling of the river in parallel with the collection of ADCP profiles to provide the basis for calibration. The physical samples would need to be analysed for mass and grain-size.

The collection of accurate suspended sediment samples requires sampling over the entire depth of the water column, and across the cross-section. To do this accurately, the monitoring instrument needs to be able to sample the water column without altering the hydraulic characteristics of the depth being monitored. This is the only way that material such as sand can be accurately collected. This is of critical importance, and only a very limited number of instruments can achieve this. Approaches that use water quality monitoring devices, such as Van Dorn or Niskin bottles are not suitable for sediment monitoring because they disturb and alter the water flow and hydraulics of the water being monitored, which alters the concentration of sand in the water column. These instruments collect unrepresentative samples. Given the high cost associated with the mobilisation of a field party to collect suspended sediment samples (boats, engines, people, fuel, and travel time, etc.), the analytical costs, and the importance of the management decisions to be based on the information, the additional relatively small initial investment of an instrument that collects accurate data is warranted.

Instruments developed over decades by the United States Geological Survey are the only instruments that have been scientifically proven to accurately collect suspended sand in rivers. They are designed such that the hydraulics of the water column at the point of collection are not altered, and are weighted such that the water entering the nozzle is moving at the same rate at which the instrument is moving in the river. Two different versions of these instruments are available:

- Depth-integrating — This instrument is continuously deployed from the surface to the bed and back to the surface at a pre-determined rate, such that the water column is sampled in proportion to the flow rate; more water is collected at depths at which flow rates are high as compared to depths where flow rates are low. The deployment of this instrument requires a very large and powerful variable-speed winch, which unfortunately are very costly and frequently need to be custom built.
- Point-integrating — This instrument has an electronically operated nozzle that opens and closes. It is deployed to a fixed depth, and then the nozzle is opened and remains open for a fixed time that is determined by the flow rate. At the end of the sampling time, the nozzle is closed and the sampler is raised to the surface. This instrument is required to be connected to a conducting cable, but can be deployed using any type of winch. The samples can be combined or analysed individually, to provide detailed information about the sediment being transported at that specific depth.

In the Ayeyarwady, where the aim of physical sampling is to monitor sediment transport and serve as the basis for calibrating of ADCPs, the point-integrating approach is recommended for the following reasons:

- The method will provide detailed information about sediment transported at specific depths in the river. This information can be linked to a specific ADCP signal for calibration.
- The implementation requires fewer calculations in the field. Prior to deployment of the depth-integrating instrument, several calculations are required based on the velocity and depth of the water column. These include determinations of the size of the nozzle and the rate at which the instrument needs to be lowered and raised, and the adjustment of the winch to achieve these rates. Although not overly difficult, the deployment of a point-integrating instrument is more straightforward, as the time the nozzle is to be opened only needs to be determined, based on the water velocity at the monitoring depth.
- The point-integrating method does not require a high cost variable-speed winch. This is a very large advantage as the procurement of these winches is difficult, and providing an adequate power source for the variable speed winches adds additional cost and complexity to implementation. The point-source instrument can be raised and lowered manually if required and because the nozzle is closed, the rate at which the instrument moves through the water column is not important.

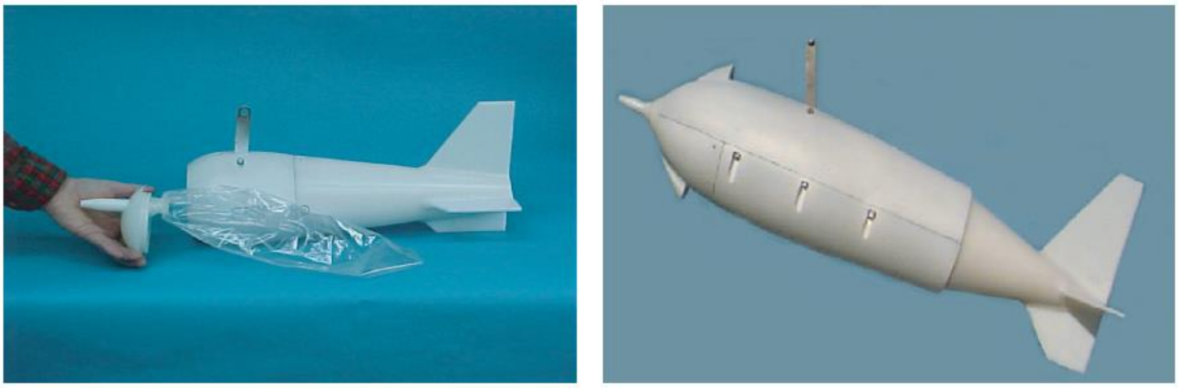


Figure 6.7 - Photos of depth integrated suspended sediment samplers

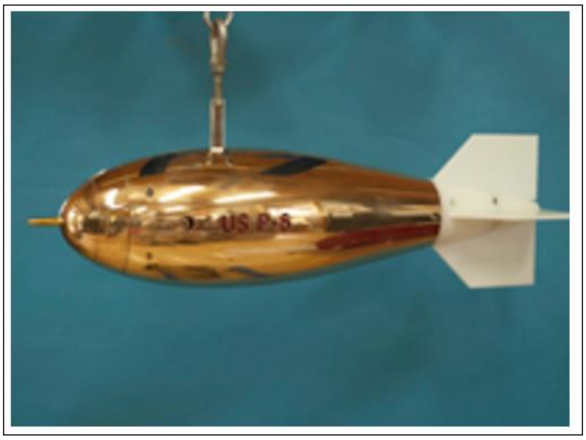


Figure 6.8 - Photo of point-integrating suspended sediment sampler

6.6.3 Bedload monitoring

ADCP technology can also be used to estimate bedload transport. ADCPs determine discharge by establishing the movement of water relative to a reference frame. Most ADCPs now use a reference provided by GPS readings collected at the same time as the measurement is made. However, the instrument can also use the riverbed as a reference frame. If the bed is moving due to bedload transport of sediment while a measurement is made, there will be an inherent inaccuracy in the measurement if the bed is used as the reference frame. This inaccuracy, which is directly related to the velocity at which the bed is moving, can be easily quantified in the field and used to estimate the rate of bedload movement (Yorozuya et al., 2010). This information, combined with grab samples of the bed material (a monitoring technique described in the next section) at the time of monitoring, can provide a good understanding of bedload transport.

Other physical samplers that can be used to measure bedload (e.g. BL-84) are very difficult to deploy in large rivers, and results tend to be highly variable, depending on where on the riverbed the sampler is located relative to moving bedforms (e.g. sand waves or dunes). These techniques are not recommended for the Ayeyarwady.

6.6.4 Bed material monitoring

Collecting bed material is required to quantify bedload transport, and to understand how the bed of the river changes spatially and seasonally. Grab samples of bed material collected across the river also provide an understanding of how the variability of flow affects bed material deposition. The collection of bed materials under conditions of high flow requires a weighted instrument, such as the BM-54 shown in

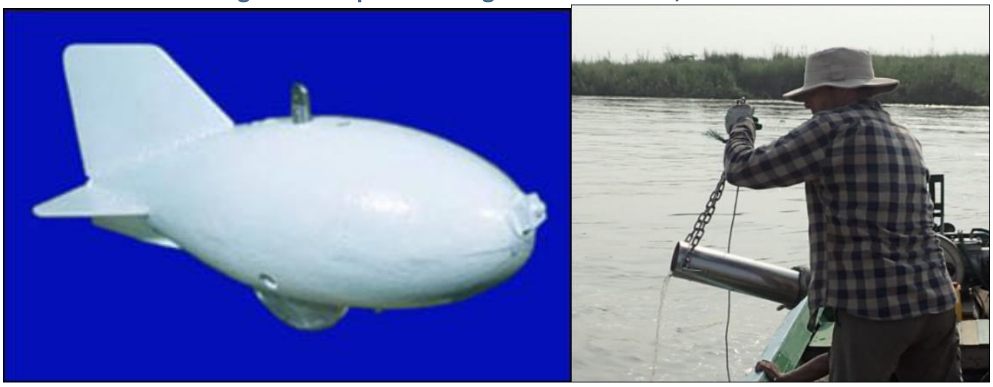


Figure 6.9 that captures sediment upon contact with the bed of the river, or the low-cost alternative pipe-dredge that collects sediment as it is dragged behind a boat floating at the speed of the current.

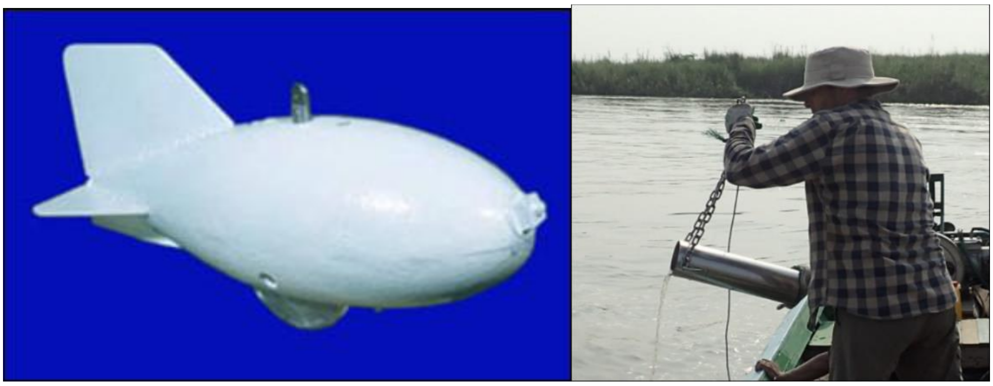


Figure 6.9 - Potential bed material monitoring equipment (left) Spring loaded BM-54 bed material sampler that collects sediment son contact with the river bed (right) Pipe dredge used for collecting bed materials by SOBA Package 3 team.

6.6.5 Large-scale catchment monitoring

Large-scale geomorphic monitoring such as provided by repeat surveyed river cross-sections, long-sections, or the analysis of satellite imagery, is warranted to provide a context within which the local sediment transport results can be translated. These techniques should be implemented basin-wide to understand how different areas are changing and what that might mean for the river. Special attention should be directed to systematic monitoring of the delta and delta front, and channel migration patterns. This GIS-based activity is applicable to several of the indicators identified by SOBA Package 3 and other packages. It is not included in the rest of the sediment monitoring discussion, but methodologies for satellite analysis are included in Annex 3.

6.7 Outline of Potential Monitoring Sites, Indicative Equipment Costs, and Time Requirements for Sediment Monitoring

6.7.1 *Potential monitoring sites and frequency*

The aim of sediment monitoring is to establish where and when sediment is entering the main stem of the river and moving through the system. To achieve this, it is necessary to have monitoring locations upstream and downstream of major tributaries, and at regular intervals along the main stem. Because sediment measurements depend on accurate discharge measurements, sediment monitoring should coincide with gauging locations. Figure 6.10 shows tentative monitoring locations on the main stem of the Ayeyarwady that coincide with gauging sites and would provide good coverage. Ideally, several sites within the Chindwin would be included, as would major tributaries, such as the Shweli, Myitnge, and Mu. Input from tributaries can be estimated by difference using the results from upstream and downstream of the tributary mouth, but direct measurements can be more accurate, especially in areas where the Ayeyarwady is braided. The tentative monitoring locations include 10 sites on the main stem of the Ayeyarwady and 3 in the Chindwin. The recommended tributary sites (Shweli, Myitnge, and Mu) would increase the sample numbers to 16. The actual number and locations of tentative monitoring sites is a topic for discussion during the planning phase of the project.

Monitoring frequency will be dependent on the frequency of hydrologic monitoring, but as a starting point is recommended as weekly during the peak wet season, fortnightly during the shoulder months and monthly during the dry season, for a total of 31 samples per year, as indicated in Table 10.

Table 10 - Proposed sediment sampling frequency

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1	1	1	2	2	4	4	4	4	4	2	2

The total number of individual suspended sediment samples requiring analysis will be 16 sites x 15 samples per site x 31 sampling runs, or 7,440 samples per year. The number of bed material samples requiring analysis will be 16 sites x 2 samples per site x 31 sampling runs, or 992 samples per year. This high intensity of sampling is recommended to be implemented for at least two years to obtain a comprehensive dataset of sediment transport in the river, and to provide a sound basis for calibrating ADCP to measure sediments.

6.7.2 *Indicative monitoring time*

As proposed, the initial suspended and bedload sediment monitoring would be completed in conjunction with hydrologic monitoring, using an ADCP to record the river cross-section and discharge. This initial work is based on the collection of physical water samples for suspended sediment analysis. In addition to the ADCP sections collected for hydrologic monitoring, the following activities would be required:

- The completion of an ADCP loop-test that consists of crossing the river and returning to the same location with the ADCP recording in bottom-tracking mode. This provides the necessary information for estimation of bedload.
- The collection of up to 15 point-integrated suspended sediment samples. At five locations across the cross-section, samples are collected from three depths (0.2, 0.6, and 0.8 of the depth of the river) while the boat is held stationary, either by motor or anchor. Each sample requires the lowering of the suspended sediment sampler to a pre-set depth, opening the valve for a set length of time, closing the valve and raising the sampler. The sample is then transferred into a sample bottle for subsequent suspended sediment and grain-size analysis.
- The collection of bed material for grain-size analysis for use in determining bedload transport rates.

It is estimated that the collection of the additional ADCP transect and samples will require three to four hours of field time per site. More time will be required in the wet season when the river is higher as compared to the dry season.

If a reliable calibration between ADCP backscatter results and suspended sediment concentrations can be derived, then sampling will be faster as only the bedload component would be required. Similarly, if an instrument that can measure in situ suspended sediments and grain-size is available, then sampling time would be reduced.

6.7.3 Indicative equipment and analytical costs

Each hydrographic team completing suspended sediment monitoring will require the equipment described in Table 11. It is important that each team has equipment such that the river can be monitoring in different locations on the same date, thus providing an accurate picture of sediment transport.

Additional equipment useful for calibrating and obtaining detailed grain-size distribution and mass is an in situ analyser. These instruments are lowered through the water column and provide a continuous measurement of the sediment mass in suspension and the grain-size distribution of the material. There are several options that range in price from ~$35,000 USD to ~$45,000 USD. One approach would be to have one or two of these instruments for the basin, which could be rotated through the monitoring locations and used to provide rapid, site-specific information to refine the ADCP calibration.

The sediment monitoring regime will generate a large number of samples, estimated at about 8,000 suspended sediment samples and ~1,000 bed material samples for the determination of bedload. If additional bed material sampling is completed, then the sample numbers will be higher. There are two options for analyzing this large number of samples: develop sediment analysis laboratories within the agency responsible for ongoing monitoring, or out-source the samples to high-quality laboratories. Some indicative costs associated with equipment for establishing a laboratory are provided in Table 11. Quotations obtained by SOBA 3 for the analysis of suspended sediment samples and grain-size determination are presented in Table 12 for information. It is possible that analytical costs could be lower for such a large number of samples.

Whether the samples are analysed in house or under contract, it is imperative that accepted methods are applied, and stringent QA/QC controls implemented. It is also recommended that a laser particle size analyser is used for the determination of grain-size. This technology is not available in commercial laboratories within Yangon, based on the experience of SOBA 3.

Table 11 - Equipment for integrated sediment monitoring

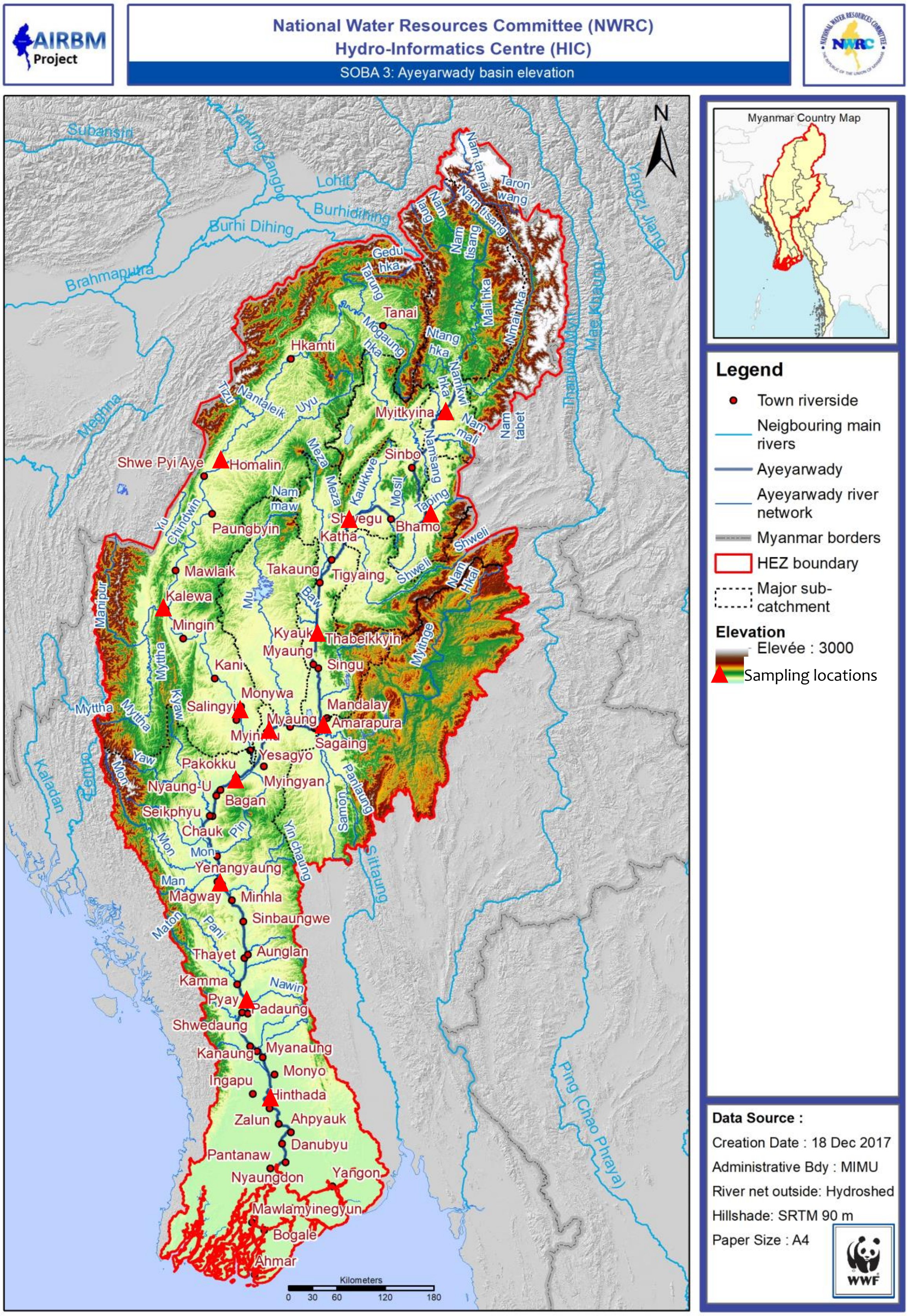
Equipment for each Hydrographic Team	Use	Indicative Cost	Comment
Boat and safety equipment	Hydrologic and sediment monitoring.	Assumed to be part of hydrologic monitoring equipment.	Safety is a primary concern. The deployment of equipment from boats in fast-flowing rivers has inherent risks; having a suitable boat with safety equipment needs to be the top priority.
ADCP	Bedload monitoring, collection of profiles for discharge measurement, collection of profiles for	Assumed to be part of hydrologic monitoring equipment.	A backup ADCP should be available for deployment at short notice.

Equipment for each Hydrographic Team	Use	Indicative Cost	Comment
	sediment interpretation.		
Winch and power source (generator or on board power supply)	Deploying suspended sediment and bed material monitoring equipment.	To be locally sourced.	Requires a power supply sufficient to lift a 100 kilogram sampler and collect at least 15 samples.
Suspended sediment sampler	Collection of point-integrated suspended sediment samples (e.g. United States Geological Survey P6-200).	~$10,000 USD, including conducting cable.	Large size sampler required due to depth and flow velocity of river.
Bed material sampler	For collection of bed material to determine bedload transport.	~$3,000 USD	May require second small winch for deployment.
Small winch for bed material sampler	For collection of bed material to determine bedload transport.	To be locally sourced.	Can be hand or power driven. Needs to lift ~40 kilograms.
Mounting brackets, storage boxes, sample bottles, containers, GPS, etc.	For installation of equipment.	Up to ~$2,500 USD	Installation of equipment on boat.
Additional Equipment			
In situ particle grain-size analyser	Provides continuous profiles of the mass and grain-size of suspended sediment. New instruments may also provide water velocity.	~$35,000 to $45,000 USD	Would be useful to have one or two in the basin that could be rotated between sites.
Laboratory equipment for sediment analysis	Filtration equipment, accurate balance (to minimum four decimal places), climate control for laboratory, etc.	~$20,000 USD-very rough estimate and depends on existing equipment and facilities	This equipment is required if agencies are to complete sediment analyses ‘in house’.
Grain-size analyser	To rapidly and accurately determine grain-size distribution.	~$10,000 USD A wide range of options are available	There are a range of options.

Table 12 - Indicative costs for suspended sediment and grain-size analyses in Yangon

Analysis	Estimated Cost	Comment
Suspended solids	10,000 kyat/sample	This analysis used glass fibre filters. Would recommend cellulose acetate filters that have a smaller nominal pore size to ensure capture of the finest-grained sediment.
Grain-size distribution	20,000 kyat/sample	Using sieve analysis and hydrometer (settling) methods.

Figure 6.10 - Potential sediment mining sites in the Ayeyarwady River basin



6.8 Summary of Proposed Strategy

The following graphic summarises the proposed sediment monitoring strategy. The project will include a minimum two-year period of intensive sediment monitoring. During this period, the methods and protocols for sediment collection, analysis and data reporting, and management will be established. Inter-agency capacity building is a critical component of this period, to ensure that the same sediment collection methods are uniformly adopted by different user groups.

Based on the results collected over this two-year period, ADCP results will be calibrated with the suspended sediment results. Integrating this information with accurate discharge measurements will allow the rapid collection and determination of suspended sediment concentrations and loads using ADCP only. Bedload movement will be estimated using the ADCP output combined with local bed material grab samples.

The long-term strategy includes periodic checking of the ADCP suspended sediment calibrations. This is to ensure that as land and river uses change, that any changes to the characteristics of the sediment being transported are recognised and reflected in updated calibration curves.

The strategy also includes a biennial review of available sediment monitoring equipment, techniques and strategy. There is an increasing move towards remote sensing techniques for measuring sediment concentrations and sediment grain-size distributions in situ, and evaluating the potential and cost of these technologies should be periodically reviewed. Monitoring sites and sampling frequencies should also be reviewed to ensure that relevant information is collected in the most cost-effective manner.

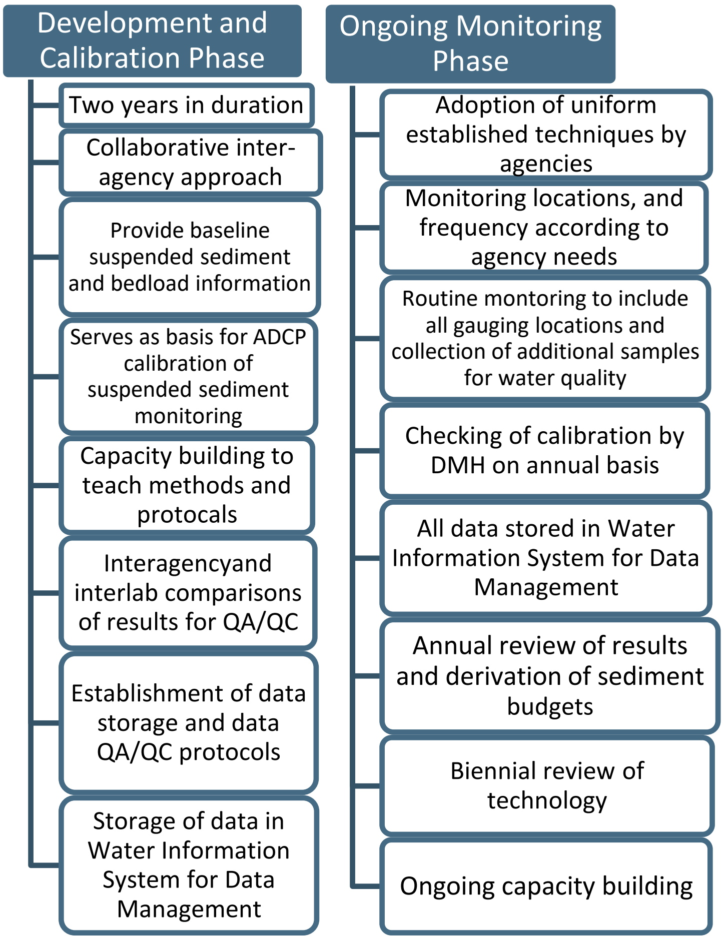


Figure 6.11 - Summary of proposed integrated sediment monitoring in the Ayeyarwady.

6.9 First Steps

The recommended first step towards developing and implementing an integrated geomorphic and sediment monitoring system in the Ayeyarwady is to hold a workshop of relevant agencies/teams to discuss sediment data needs and future directions. Potential discussion topics for such a workshop include, but are not limited to:

- Overview of existing sediment monitoring
- What information is required to be provided by sediment monitoring?
- What is the status and future plan with respect to the implementation and training of ADCP use for discharge analysis?
    - Field methods used
    - Data management and interpretation techniques
    - Is it feasible to integrate sediment monitoring into discharge monitoring activities?
    - What sites and monitoring frequency is adopted for discharge measurements?
- Sediment monitoring techniques; pros and cons of different approaches
- Availability and condition of existing equipment
    - Boats
    - Samplers
    - Winches/power supply
    - Safety issues
- Capacity building and training
- Linkages with water quality monitoring
- Identification of next steps

7. OTHER INFORMATION GAPS AND RECOMMENDATIONS

7.1 Future Geomorphic and Sediment Monitoring

Recommendations for suspended, bedload, and bed material monitoring were provided in the previous section. This information is useful and necessary to better understand the Ayeyarwady River system, but understanding the context within which the sediment transport occurs increases the value of the sediment monitoring results. The following areas of monitoring and approaches are recommended:

- Repeat channel cross-sections over a range of water levels at the gauging stations, and at other stations where river changes or modifications may be occurring. Understanding how/if the channel is changing is critical for maintaining the accuracy of discharge-level rating curves. In addition, it provides an understanding of the long-term trend of the river with respect to channel morphology and bed level elevation. Sections are recommended to be obtained several times per year at riverine sites and in the delta.
- Establishment of a systematic methodology for mapping land and river use changes. Understanding changes to the landscape is key to understanding river responses. Standard methods for the periodic analysis of satellite images should be established so data is usable across a range of applications. Guidance as to the scale of imagery used and the scale at which changes are mapped should be established, and periodically reviewed. Activities to be targeted should include: deforestation, terrestrial mining, sand and gravel extractions of sites in the river, dredging locations and volumes, changes to the delta front, and changes to channel infrastructure such as retaining walls, groynes, etc.
- Improving databases related to water and land use would enhance the understanding of how these activities have the potential to alter the river. Ideally, information compiled would allow development of a detailed water balance of the basin. Information gaps include:
    - The locations, dam heights, impoundment volumes, and operating regimes of hydropower schemes, including small (<30 MW) projects;
    - The locations, weir/dam heights, impoundment volumes, and operating regimes of irrigation schemes;
    - The locations and descriptions of irrigation schemes that extract water directly from the Ayeyarwady, including the volumes and timing of extractions;
    - The locations and volumes of ground water extraction; and
    - The locations of all DWIR (and other) river engineering structures, such that these could be considered within the context of the geomorphic zones, and the efficacy of the works could be assessed.
- This mapping could in turn be assessed against dredging locations and the geomorphic zones (Section 2.6).
- Information that would enhance the value of the sediment monitoring information and allow sediment and nutrient balances of the river to be established:
    - The locations, numbers of operators, volumes extracted, and target sediment sizes of sand and gravel mining activities throughout the Ayeyarwady and its tributaries; and
    - The relationship between sediment size and nutrient content at different points in the river on a seasonal basis. Understanding the nutrient grain content by grain-size would promote a better understanding of the quantity of nutrients likely to be trapped in impoundments, and the timing of nutrient transport in the river.

- Collection of meteorological information that would assist analysis. This includes parameters such as rainfall total and rainfall intensity. Rainfall intensity is particularly important for understanding the episodic transport of sediment.
- Information that would enhance the understanding of deltaic processes:
  - Rates of sediment deposition, erosion, and subsidence of the delta, using methods such as those applied to the Mekong Delta (Anthony et al., 2017b);
  - Mapping coastal currents to understand the dispersal of sediments within the coastal zone and where/when currents can contribute to erosion of the delta front; and
  - Mapping of salinity intrusions. This is not really a geomorphic issue, but is closely linked with channel depth and morphology.

7.2 Recommendations

Recommendations arising from the SOBA 3 review of available information and field investigations include:

- The collection of accurate flow, sediment transport, and other geomorphic information is imperative, and should be initiated as soon as possible. The Ayeyarwady catchment is undergoing many changes at a rapid pace and there is a lack of accurate information available to quantify, or understand these changes. The reliance on historical sediment datasets for which there is no information as to their origin or accuracy will not provide the understanding required to underpin sustainable management planning or decisions. Bad data are frequently worse than no data, and the collection of current, accurate data is urgent. Ultimately the accurate information can be used to develop and calibrate hydrologic and sediment transport models, but in the short-term the collection of accurate field measurements should be the top priority.
- The implementation of monitoring should be prioritised, with easily achievable monitoring implemented rapidly. This includes the collection of accurate discharge measurements, and sediment sampling at multiple depths across the river profile using equipment that collects accurate samples.
- Monitoring should be extended to tributaries as well as the main stem of the Ayeyarwady. This is most important for large tributaries that are undergoing or targeted for water resource development, such as hydropower or irrigation.
- Monitoring methodologies should be standardised across agencies, universities, and other research groups such that different datasets can be integrated.
- Land use management policies and decisions should take riverine impacts at the local and catchment scale into account. Ongoing deforestation, the development of hydropower and irrigation schemes, sediment mining, and terrestrial mining are all impacting the river and are projected to increase in the future. The cumulative impacts of these activities need to be considered and managed during development, or the river is likely to suffer a ‘death by a thousand cuts’.

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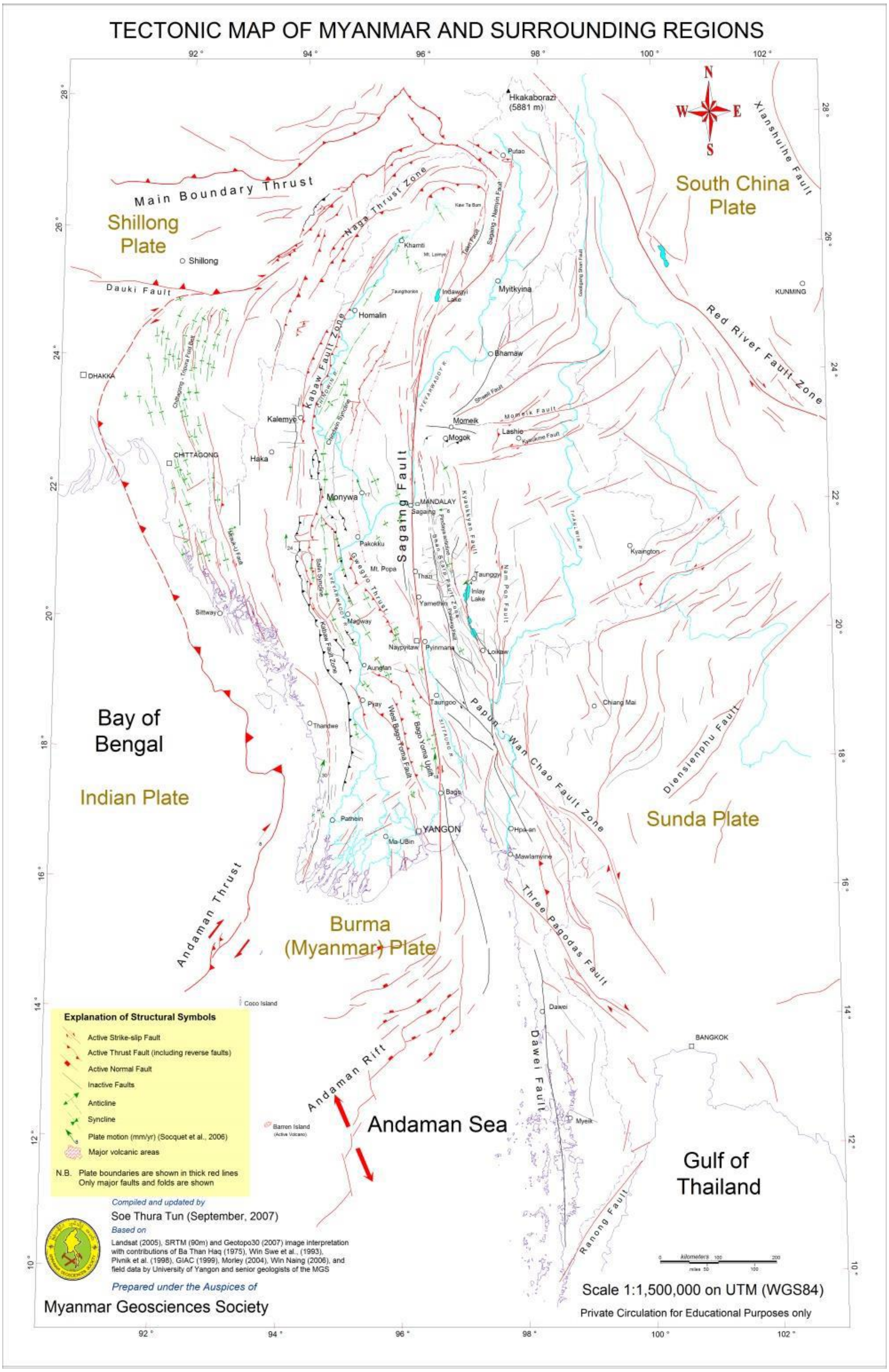
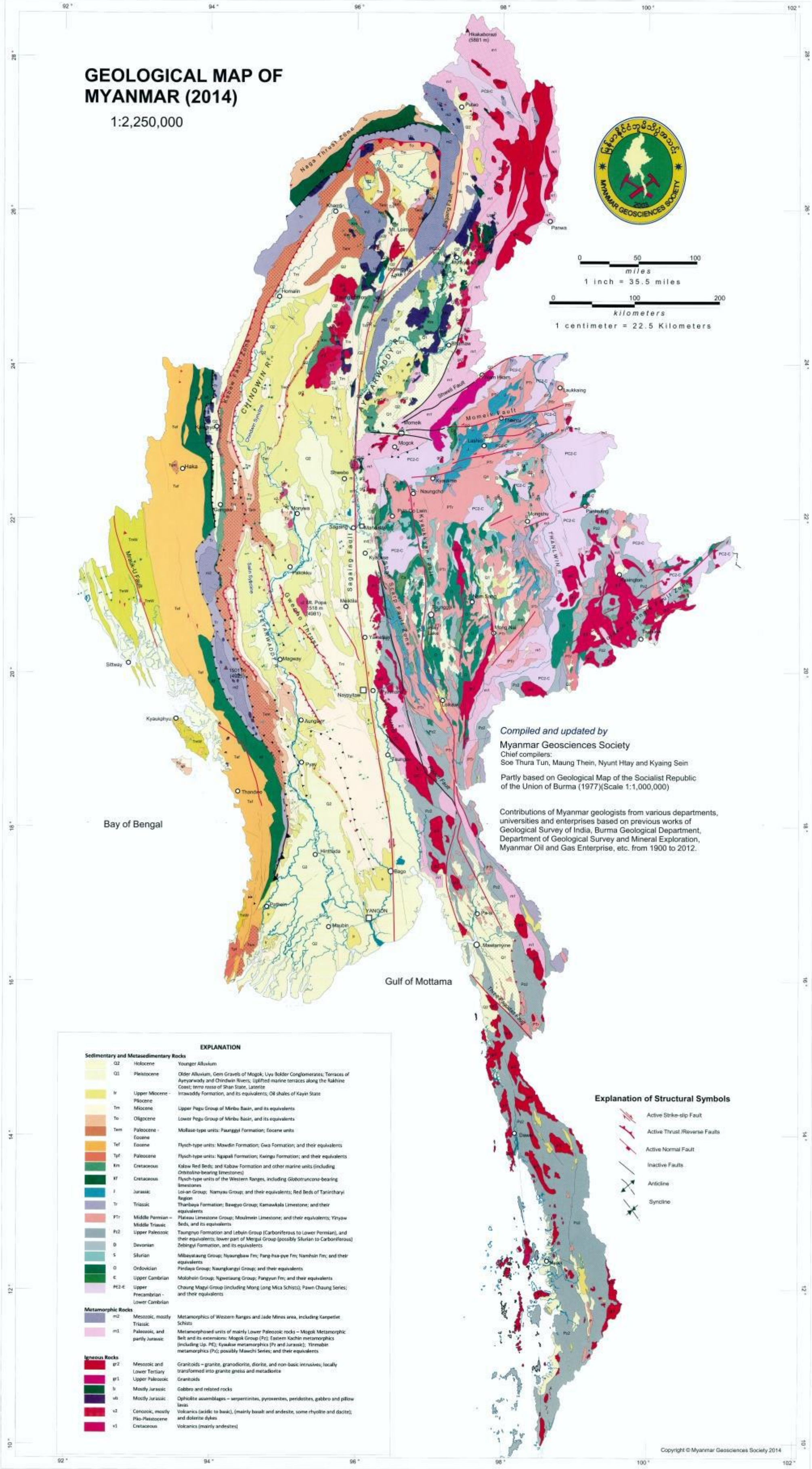
ANNEX I – TECTONIC AND GEOLOGICS MAPS OF MYANMAR


TECTONIC MAP OF MYANMAR AND SURROUNDING REGIONS
Main Boundary Thrust
Shillong Plate
Dauki Fault
Naga Thrust Zone
Kabaw Fault Zone
Sagaing Fault
South China Plate
Xianshuihe Fault
Red River Fault Zone
Momeik Fault
Papun - Wan Chao Fault Zone
Sunda Plate
Dien Bien Phu Fault
Bay of Bengal
Indian Plate
Burma (Myanmar) Plate
Andaman Thrust
Three Pagodas Fault
Andaman Rift
Andaman Sea
Dawei Fault
Ranong Fault
Gulf of Thailand
Explanation of Structural Symbols
Active Strike-slip Fault
Active Thrust Fault (including reverse faults)
Active Normal Fault
Inactive Faults
Anticline
Syncline
Plate motion (mm/yr) (Socquet et al., 2006)
Major volcanic areas
N.B. Plate boundaries are shown in thick red lines
Only major faults and folds are shown
Compiled and updated by
Soe Thura Tun (September, 2007)
Based on
Landsat (2005), SRTM (90m) and Geotopo30 (2007) image interpretation with contributions of Ba Than Haq (1975), Win Swe et al., (1993), Pivnik et al. (1998), GIAC (1999), Morley (2004), Win Naing (2006), and field data by University of Yangon and senior geologists of the MGS
Prepared under the Auspices of
Myanmar Geosciences Society
Scale 1:1,500,000 on UTM (WGS84)
Private Circulation for Educational Purposes only


GEOLOGICAL MAP OF
MYANMAR (2014)
1:2,250,000
miles
1 inch = 35.5 miles
kilometers
1 centimeter = 22.5 Kilometers
Compiled and updated by
Myanmar Geosciences Society
Chief compilers:
Soe Thura Tun, Maung Thein, Nyunt Htay and Kyaing Sein
Partly based on Geological Map of the Socialist Republic
of the Union of Burma (1977)(Scale 1:1,000,000)
Contributions of Myanmar geologists from various departments, universities and enterprises based on previous works of Geological Survey of India, Burma Geological Department, Department of Geological Survey and Mineral Exploration, Myanmar Oil and Gas Enterprise, etc. from 1900 to 2012.
Bay of Bengal
Gulf of Mottama
Sittway
Kyaukphyu
Thandwe
Haka
Homalin
Shwebo
Mogok
Magway
Naypyitaw
Pyay
Bago
YANGON
Mawlamyine
Explanation of Structural Symbols
Active Strike-slip Fault
Active Thrust /Reverse Faults
Active Normal Fault
Inactive Faults
Anticline
Syncline
EXPLANATION
Sedimentary and Metasedimentary Rocks
Metamorphic Rocks
Igneous Rocks
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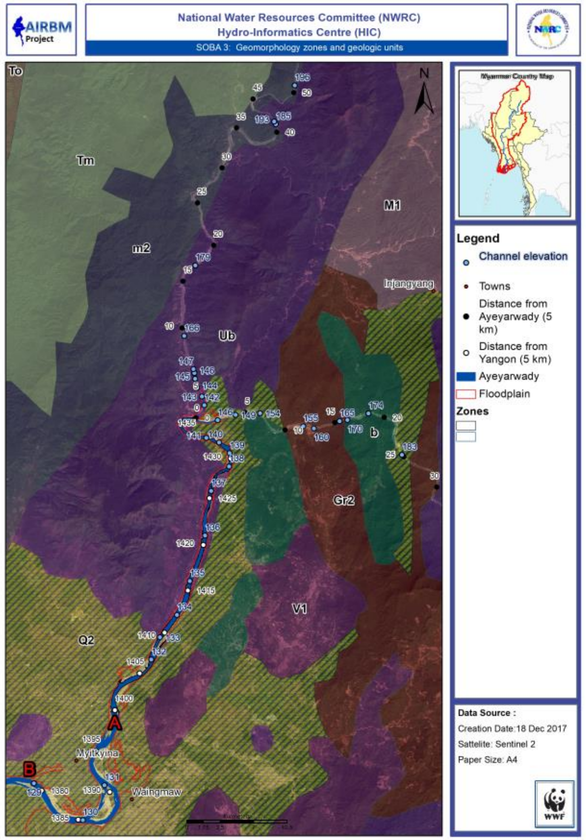
Key to Geologic Maps

	Sedimentary and metasedimentary rocks	
Q2	Holocene	Younger alluvium
Q1	Pleistocene	Older alluvium, Gem gravels of Mogok, Terraces of the Ayeyarwady and Chindwin rivers, Shan State terra rossa, Laterite
Ir	Upper Miocene-Pliocene	Ayeyarwady Formation and its equivalents
Tm	Miocene	Upper Pegu Group of Minbu basin and its equivalents
To	Oligocene	Lower Pegu Group of Minbu basin and its equivalents
Tem	Paleocene-Eocene	Molasse-type units: Paunggyi Formation, Eocene units
Tef	Eocene	Flysch-type units: Mawdin Formation, Gwa Formation and their equivalents
Tpf	Paleocene	Flysch-type units: Ngapali Formation, Kwingu Formation and their equivalents
Km	Cretaceous	Kalaw red beds and Kabaw Formation and other marine units (including Orbitolina-bearing limestones)
Kf	Cretaceous	Flysch-type units of the western ranges including Globotruncana-bearing limestones
J	Jurassic	Loi-an Group, Namyau group and their equivalents, Red beds of Tanintharyi region
Tr	Triassic	Thanbaya Formation, Bawgyo Group, Kamawkala limestone and their equivalent
PTr	Middle Permian-Middle Triassic	Plateau Limestone Group, Moulmein limestone and their equivalents; Yinyaw beds and their equivalent
Pz2	Upper Paleozoic	Thaungnyo formation and Lebyin Group (Carboniferous to Lower Permian) and their equivalents, lowe part of Mergui Group, Zebingyi formation and its equivalent
S	Silurian	Mibayataung Group, Nyaungbaw Fm, Pang-hsa-pye Fm, Namhsin Fm and their equivalents
O	Ordovician	Pindaya Group, Naungkangyi Group and their equivalents
E	Upper Precambrian	Molohein group, Ngwetaung group, Pangyun Fm and their equivalents
PE2-E	Upper Precambrian-Lower Cambrian	Chaung Magyi Group (including Mong Long micaschist), Pawn Chaung Series and their equivalents
	Metamorphic rocks	
m2	Mesozoic, mostly Triassic	Metamorphics of the western ranges and Jade mines area, including Kanpetlet schists
m1	Paleozoic and partly Jurassic	Metamorphosed units of mainly lower Paleozoic rocks, Mogok metamorphic belt and its extensions: Mogok Group (Pz), Eastern Kachin metamorphics, Kyaukse metamorphics (Pz and Jurassic), Yinmabin metamorphics (Pz), possibly Mawchi Series and their equivalents
	Igneous rocks	
gr2	Mesozoic and Lower Tertiary	Granitoids-granite, granodiorite, diorite and non-basic intrusives, locally transformed into granite, gneis and metadiorite
gr1	Upper Paleozoic	Granitoids
b	Mostly Jurassic	Gabbro and related rocks
ub	Mostly Jurassic	Ophiolite assemblages-serpentinites, pyroxenites, peridotites, gabbro and pillow lavas
v2	Cenozoic, mostly Plio-Pleistocene	Volcanics (acidic to basic), mainly basalt and andesite, some rhyolite and dacite, and dolerite dykes
v1	Cretaceous	Volcanics (mainly andesites)


AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphology zones and geologic units
Myanmar Country Map
Legend
Channel elevation
Towns
Distance from Ayeyarwady (5 km)
Distance from Yangon (5 km)
Ayeyarwady
Floodplain
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Data Source :
Creation Date:18 Dec 2017
Sattelite: Sentinel 2
Paper Size: A4
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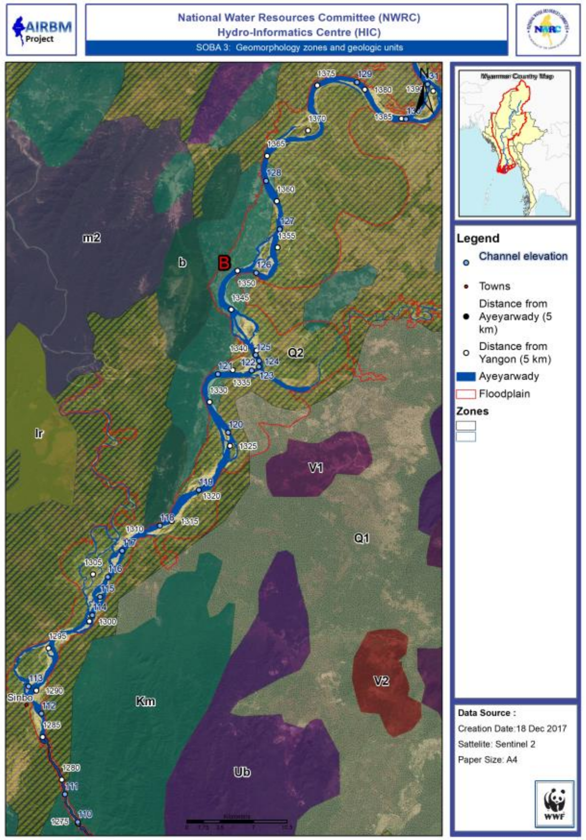
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Data Source :
Creation Date:18 Dec 2017
Sattelite: Sentinel 2
Paper Size: A4
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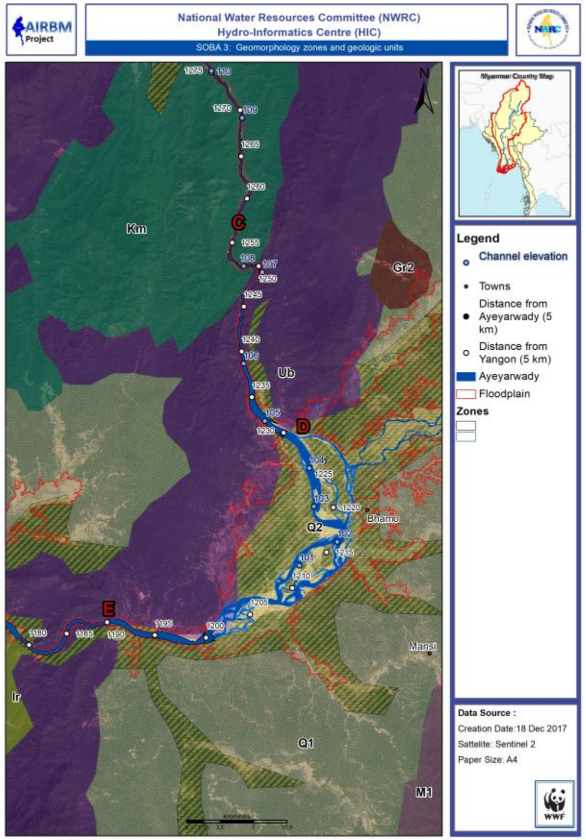
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Data Source :
Creation Date:18 Dec 2017
Sattelite: Sentinel 2
Paper Size: A4
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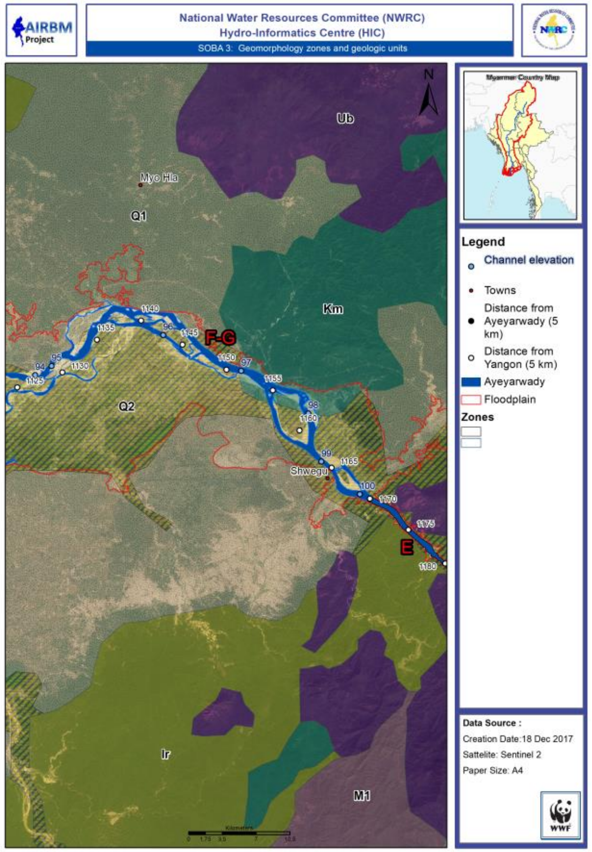
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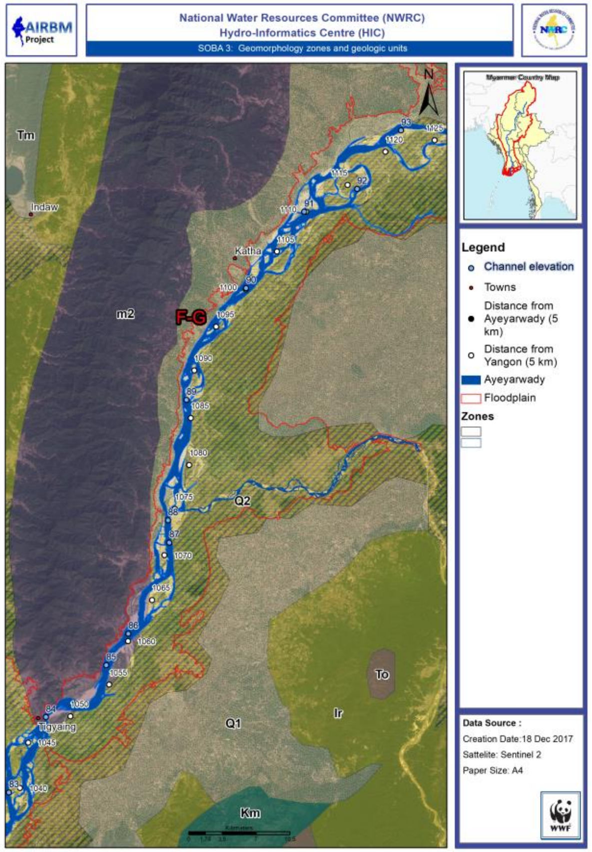
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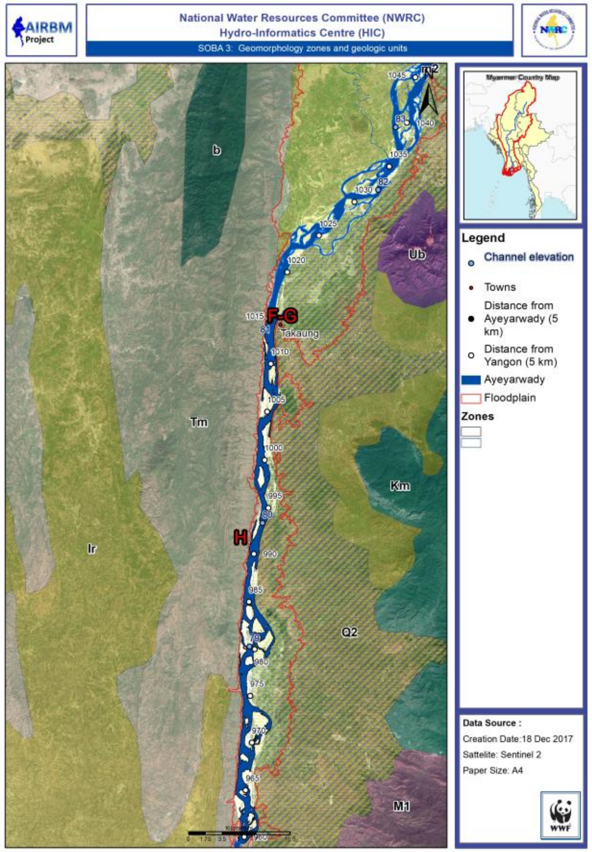
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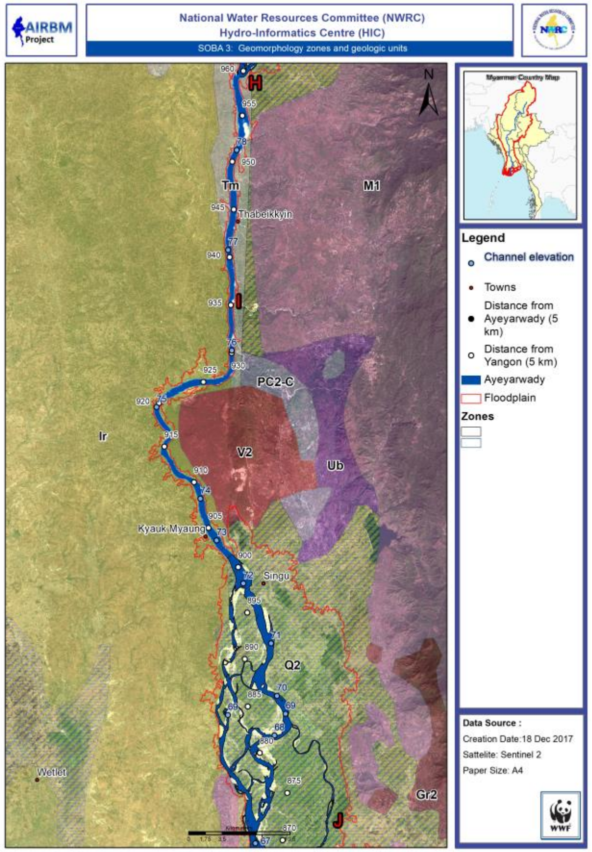
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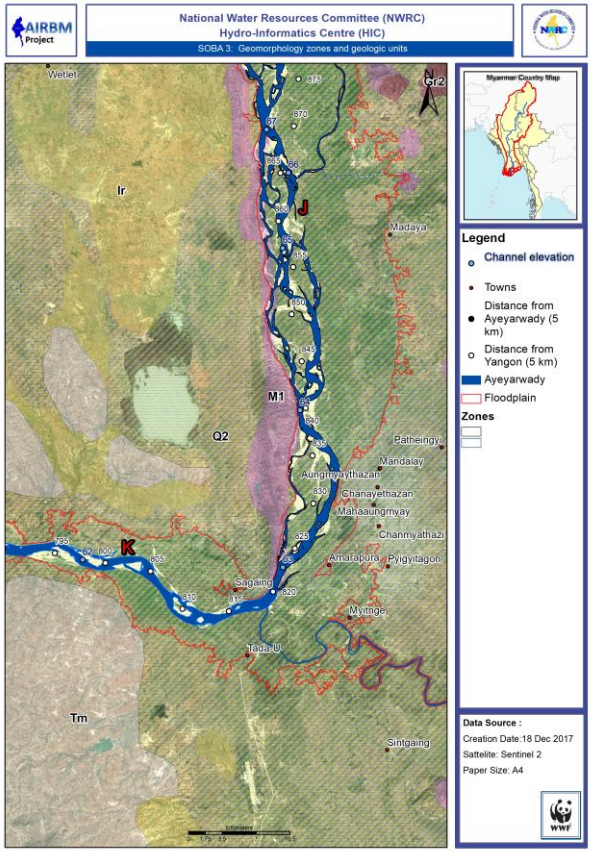
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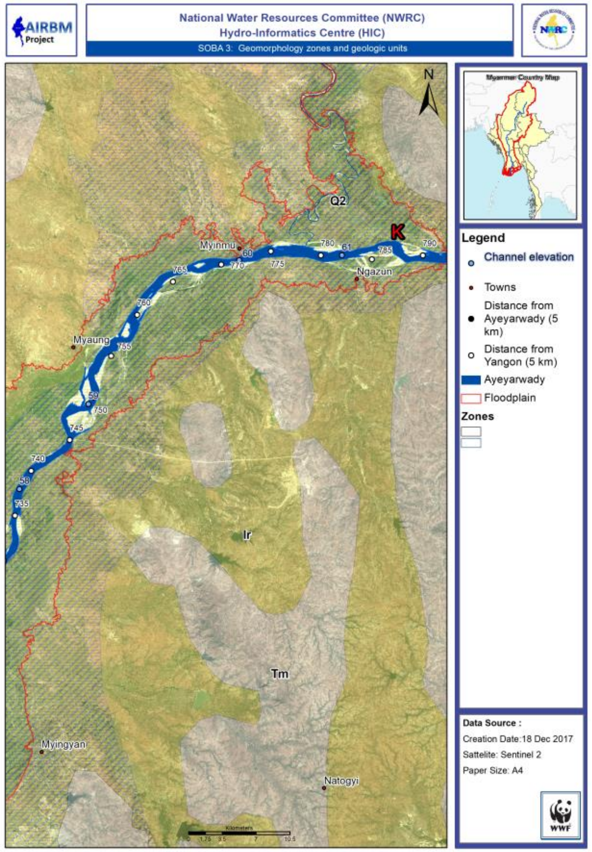
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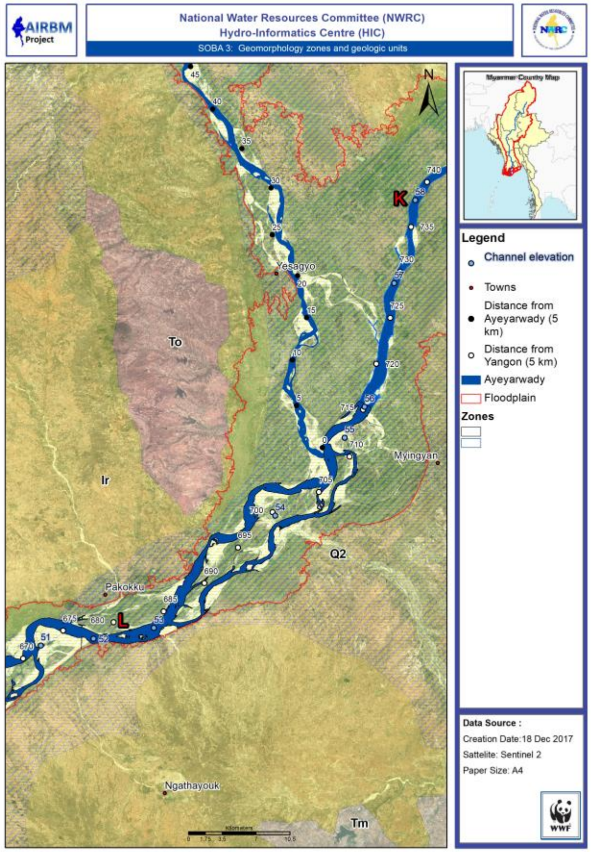
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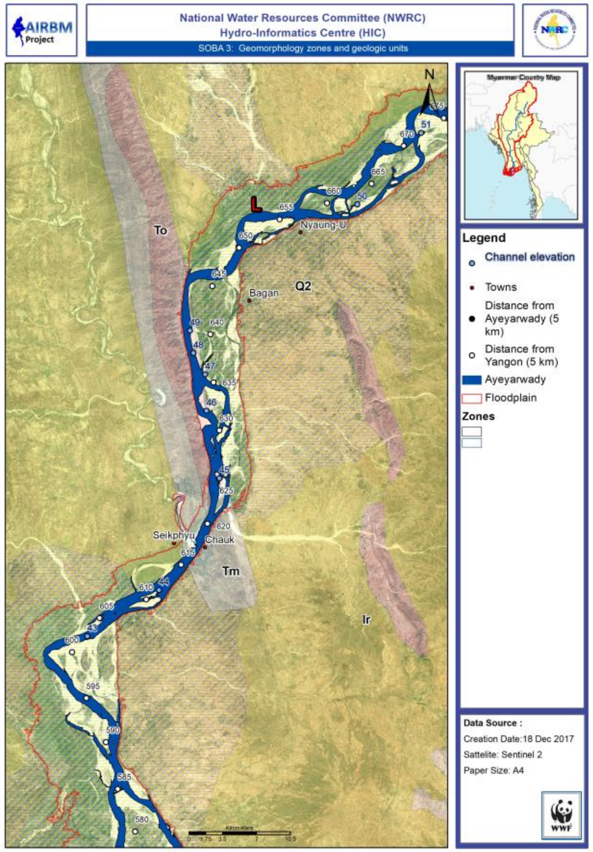
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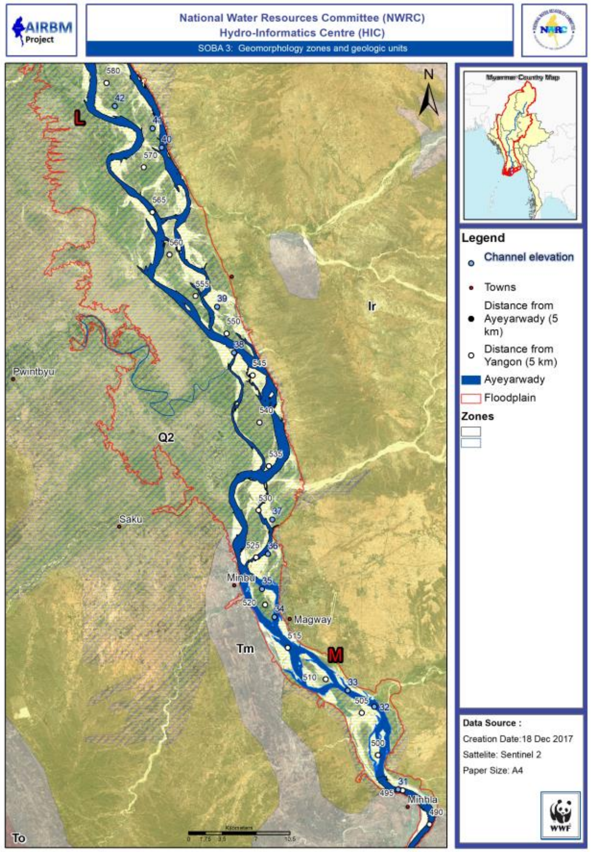
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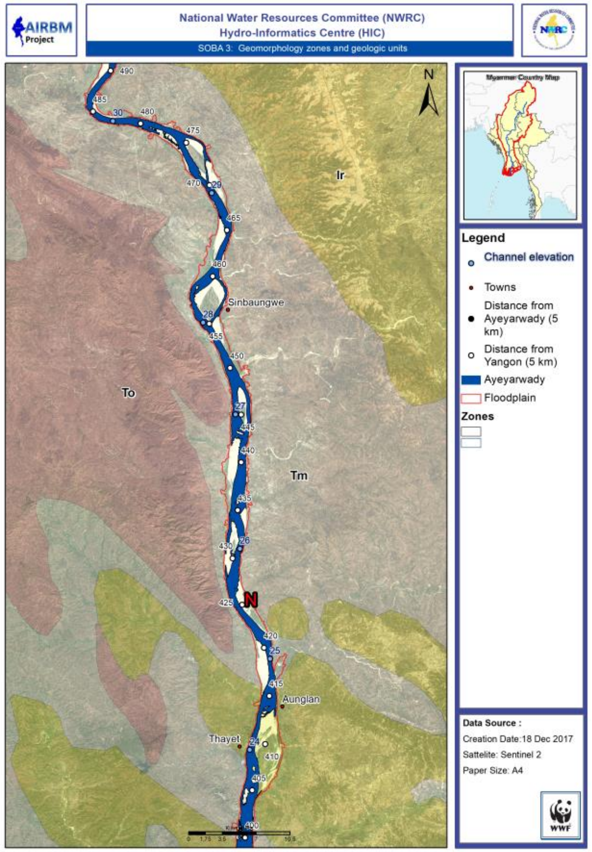
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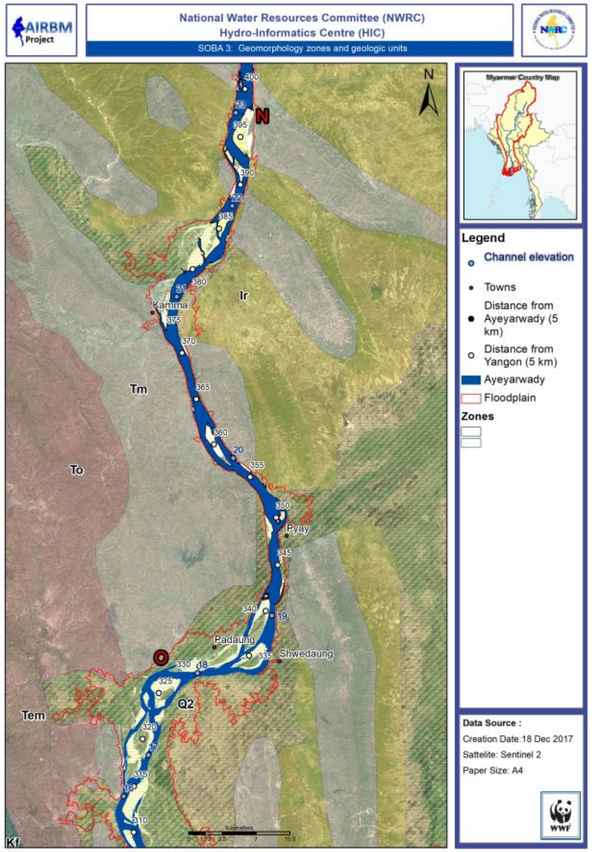
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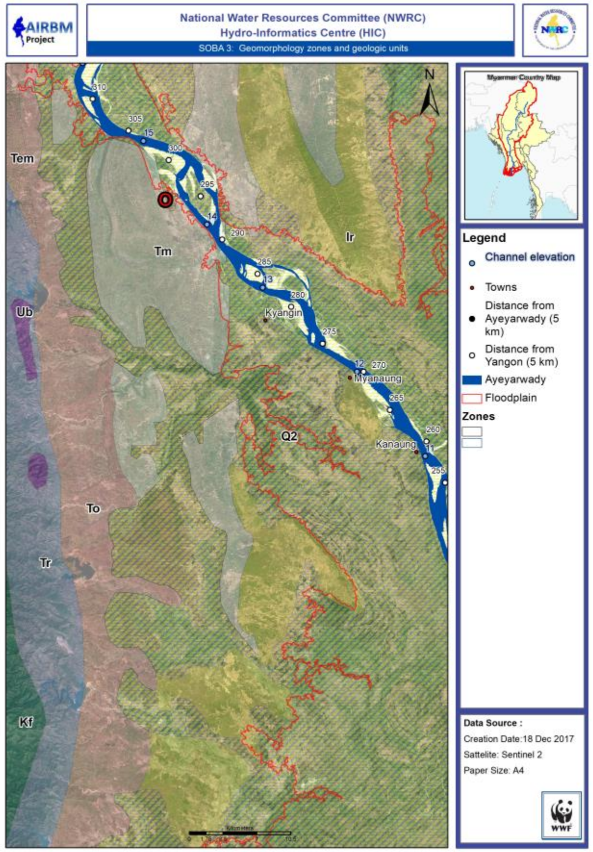
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Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphology zones and geologic units
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Zones
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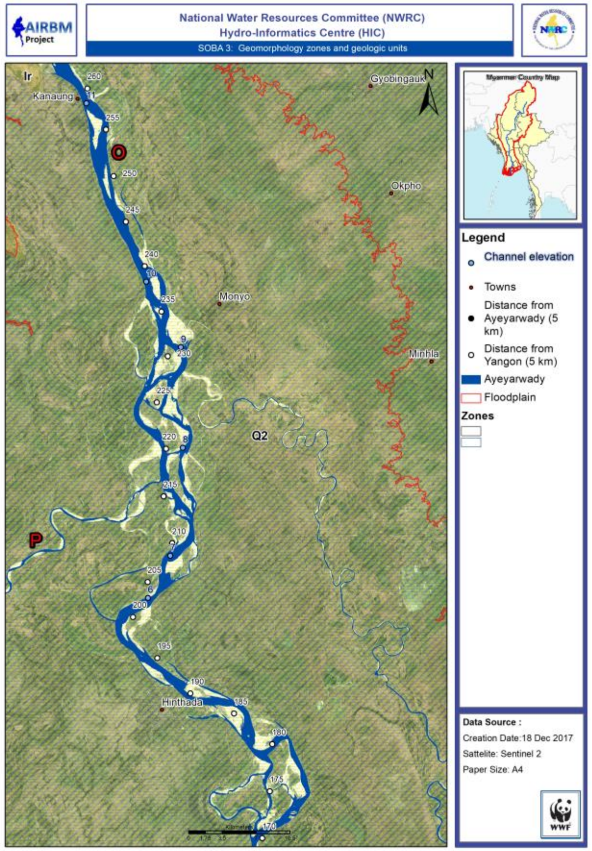

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Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphology zones and geologic units
Kanaung
Gyobingauk
Okpho
Monyo
Minhla
Hinthada
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Legend
Channel elevation
Towns
Distance from Ayeyarwady (5 km)
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Floodplain
Zones
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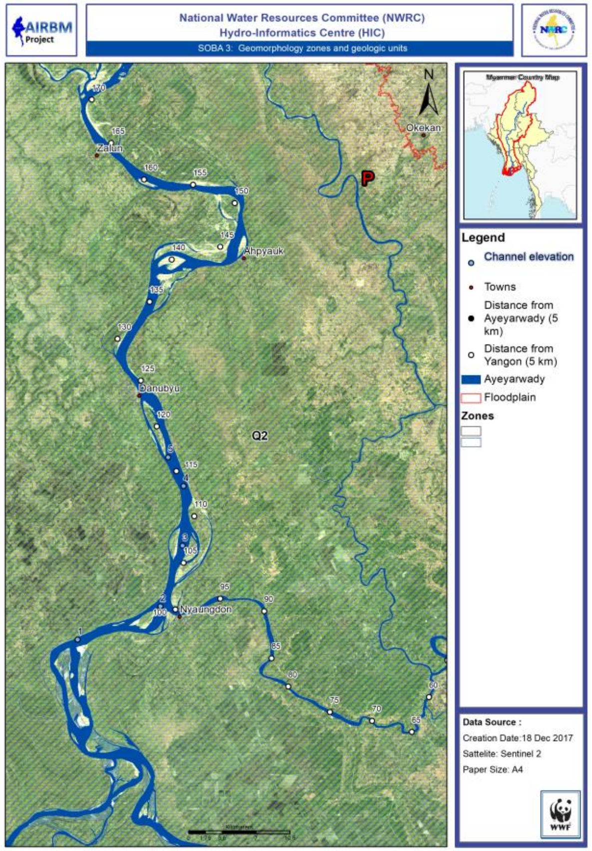

National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphology zones and geologic units
Zalun
Okekan
Ahpyauk
Danubyu
Nyaungdon
Q2
Legend
Channel elevation
Towns
Distance from Ayeyarwady (5 km)
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Ayeyarwady
Floodplain
Zones
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Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphology zones and geologic units
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Htaukkyant
Htantabin
Shwepyithar
Insein
Hlaingtharya
Mayangone
Yankin
Kamaryut
Thingangyun
Bahan
Tamwe
Sanchaung
Thaketa
Yangon
Dawbon
Pazundaung
Botahtaung
Seikkan
Dala
Seikgyikanaungto
Twantay
Kawhmu
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Distance from Ayeyarwady (5 km)
Distance from Yangon (5 km)
Ayeyarwady
Floodplain
Zones
Data Source :
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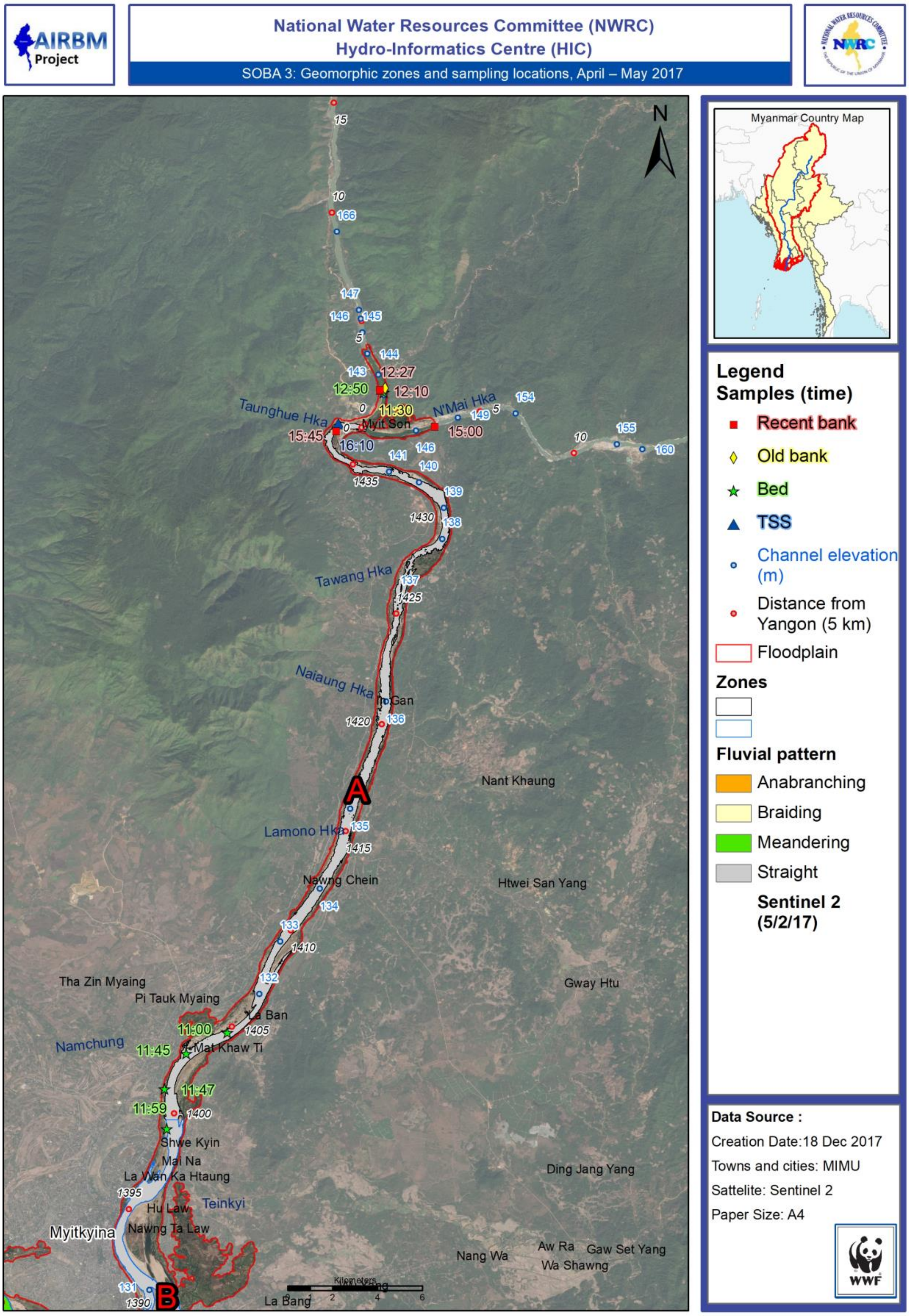
ANNEX 2 – GEOMORPHIC ZONES

Zone Descriptions

Reach	Km	Pattern type	Sub-reach start/end (km)	Sub-reach type
A	1,400 to 1,440	Sinuous confined channel	Gorge and bedrock, small point bars	
B	1,285 to 1,400	Meandering changing into braiding	B1 1,384/1,400 (16)	**Semi-confined, sinuous, lateral bars in convexities,** mid-channel islands
			B2 1,355/1,384 (29)	Unconfined, **meanders,** high sinuosity, **lateral bars with chutes** 68 to 75: large cut-off meander in floodplain (LB)
			B3 1,344/1,355 (11)	**Wandering pattern.** Mid-channel bars and islands Ancient anabranches in floodplain (LB)
			B4 1,334/1,344 (10)	**Braiding,** lateral and mid-channel bars Cut-off meanders including former sandbars (102) in LB
			B5 1,285/1,334 (49)	**Braiding** Ancient anabranches in floodplain (145 to 150)
C	1,229 to 1,285	Straight confined channel	C1 1,237/1,284 (47)	Bedrock outcrops on banks and islands
			C2 1,229/12,381 (9)	Wider, flat bedrock channel. Lateral sandbars
D	1,200 to 1,229	Braided channel and complex floodplain	D1 1,224/1,229 (5)	Unconfined or semi-confined channel
			D2 1,200/1,224 (24)	Ancient anabranches and active flood channel with sandbars in floodplain (LB) Lakes and marshes (219 to 221) fed by active anabranches (RB) Ancient meander belt with fields and forest (222 to 232)
E	1,169 to 1,200	Confined bedrock channel		
F	1,100 to 1,169	Anabranches with two to three braided channels	F1 1,140/1,169 (29)	Semi-confined active channel, floodplain with lake (275 to 283)
			F2 1,100/1,140 (40)	Unconfined, wide and shifting active channel. Anabranches displaying second-order in-channel braids suggesting active sediment transfer Large floodplain with ancient (inactive) meanders and anabranches Ancient network of inactive anabranches in floodplain Broad wetland on LB
G	1,014 to 1,100	Semi-confined braiding and limited active anabranching	Semi-confined channel (bedrock on RB). Stable lateral islands, mobile bars in active channel Limited anabranching (382 to 387) Cut-off meander (405 to 414), ancient lateral cut-off anabranches Active anabranch (410 to 417)	
H	958 to 1,014	Braiding in confined channel	H1 984/1,014 (30)	Confined channel, bedrock on LB and RB **Braiding: large flat bed with sandbars** LB: ancient channel (terrace 82 to 86 m)

<table>
<tr><th>Reach</th><th>Km</th><th>Pattern type</th><th>Sub-reach start/end (km)</th><th>Sub-reach type</th></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td>H2
966/984 (18)</td><td>Wider braided channel</td></tr>
<tr><td>H3
958/966 (8)</td><td>Confined channel</td></tr>
<tr><td>I</td><td>900 to 958</td><td>Confined bedrock channel</td><td colspan="2">Alluvial fans from tributaries and ancient lava flow.</td></tr>
<tr><td>J</td><td>819 to 900</td><td>Anabranches</td><td colspan="2">- Limited anabranching pattern with active, single-thread, braided and shifting channels (indication of large sediment transfer). Elongated short islands.
- Floodplain with ancient and stable anabranches.</td></tr>
<tr><td rowspan="2">K</td><td rowspan="2">714 to 819</td><td rowspan="2">Semi-confined braiding and local anabranching</td><td>K1 744/819 (75)</td><td>Locally confined channel. Large sandbars and cultivated islands, mostly attached to the banks with chute channels.
Transitional pattern between sinuous channel at low-flow and braided channel.
Limited anabranches: (626 to 631; 637 to 642).
Wetland on RB (680 to 685) and at the Mu River confluence.</td></tr>
<tr><td>K2 714/744(30)</td><td>Semi-confined straight channel with stretches of large floodplain. In the downstream part of the reach, limited depositional landforms (deeper channel?).
Ancient (inactive) anabranch network (688 to 708) on RB.
Active anabranches: (707 to 711) and (721 to 724) on RB.</td></tr>
<tr><td rowspan="2">L</td><td rowspan="2">521 - 714</td><td rowspan="2">Semi-confined anabranching including large braided channels</td><td>L1
604/714 (110)</td><td>Anabranching inside a constricted valley, with one to three braided channels and connections between them, large islands and active sandbars, and locally some ancient, inactive outer anabranches (728 - 735).
Remarkable importance of the Chindwin River (large sediment input) and significant inputs from the hills belonging to the Dry Zone.</td></tr>
<tr><td>L2
521/604 (83)</td><td>Anabranching inside a constricted valley with one to three flat and braided channels. Large islands, large mobile sandbars.</td></tr>
<tr><td>M</td><td>496 to 521</td><td>Semi-confined braided pattern</td><td colspan="2">Mostly actively shifting sandbars across a wide and flat channel bottom. Some (residual?) large islands covered by fresh sand (930 to 932).</td></tr>
<tr><td>N</td><td>339 to 496</td><td>A unique, narrow and stable (confined) channel</td><td colspan="2">Alternation of sinuous and straight confined stretches incised in folded bedrock. A narrow and flat channel with alluvial and size-limited landforms. However, sediment transport may be very active.
A few alluvial islands in wider reaches, some of them covered by fresh sand. Large point bars, mega-ripples locally, few island, some of them are rocky islands (967</td></tr>
</table>

Reach	Km	Pattern type	Sub-reach start/end (km)	Sub-reach type
			to 971; 983 to 987). Local anabranches around islands (1,029 to 1,037; 1,057 to 1,061 and 1,064 to 1,068).	
O	250 to 339	Semi-confined discontinuous anabranching with active braided channels	Channel incised in a wider confined valley bottom. A few rocky islands (1,102 to 1,105). The incised valley is sinuous at large scale. Anabranching (one to three channels) with large sandbars inside active braided channels. Ancient anabranches still active during floods (1,116 to 1,120, 1,127 to 1,139 and 1,153 to 1,165) and ancient wetlands (LB 1,123 to 1,128).	
P	Andaman Sea to 250	Unconfined straight braided channel	Flat and straight channel with elongated sandbars. Cut-off meanders on the left bank of alluvial plain (1,182 to 1,188 and 1,189 to 1,201). These former channels may correspond to an ancient meander pattern Other train of cut-off meanders on the RB alluvial plain (1,200). This train corresponds to a former high forming-discharge. It is not connected to any significant tributary. This suggests the role of tectonics isolating a patch of ancient meandering.	
Delta branches Q	KP 1,205 to the Indian Sea	Upstream main branch	**Wide anabranching pattern including active braided channels.** The discharge and the sediment transfer are not affected by the small distributaries on the left and right banks. Flat bed with large sandbars. Channels are sinuous inside a straight anabranching train. Meandering with sandbar on convexity which occur 65 km directly from km 1214. Traces of old meanders The distributary splits again 94 km from KP 1214 and 105 km from the sea The first distributary to the east (LB) is the smallest. The second distributary in the west (RB) connects with the third over a distance of 20 km. Wandering with sandbar (which occur until 75 km from KP 1217 in a straight line). The distributary splits again and displays an anastomosing pattern over a distance of 144 km from KP 1,217 (115 km from the sea). The third distributary is the main channel with wandering and local anabranch. Sandbars occur until 125 km from KP 1217 in a straight line. The distributary splits again and displays an anastomosing pattern over a distance of 105 km from KP 1,217 (100 km from the sea).	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National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
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Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
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Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
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Tha Zin Myaing
Pi Tauk Myaing
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Gway Htu
Shwe Kyin
Mai Na
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Hu Law
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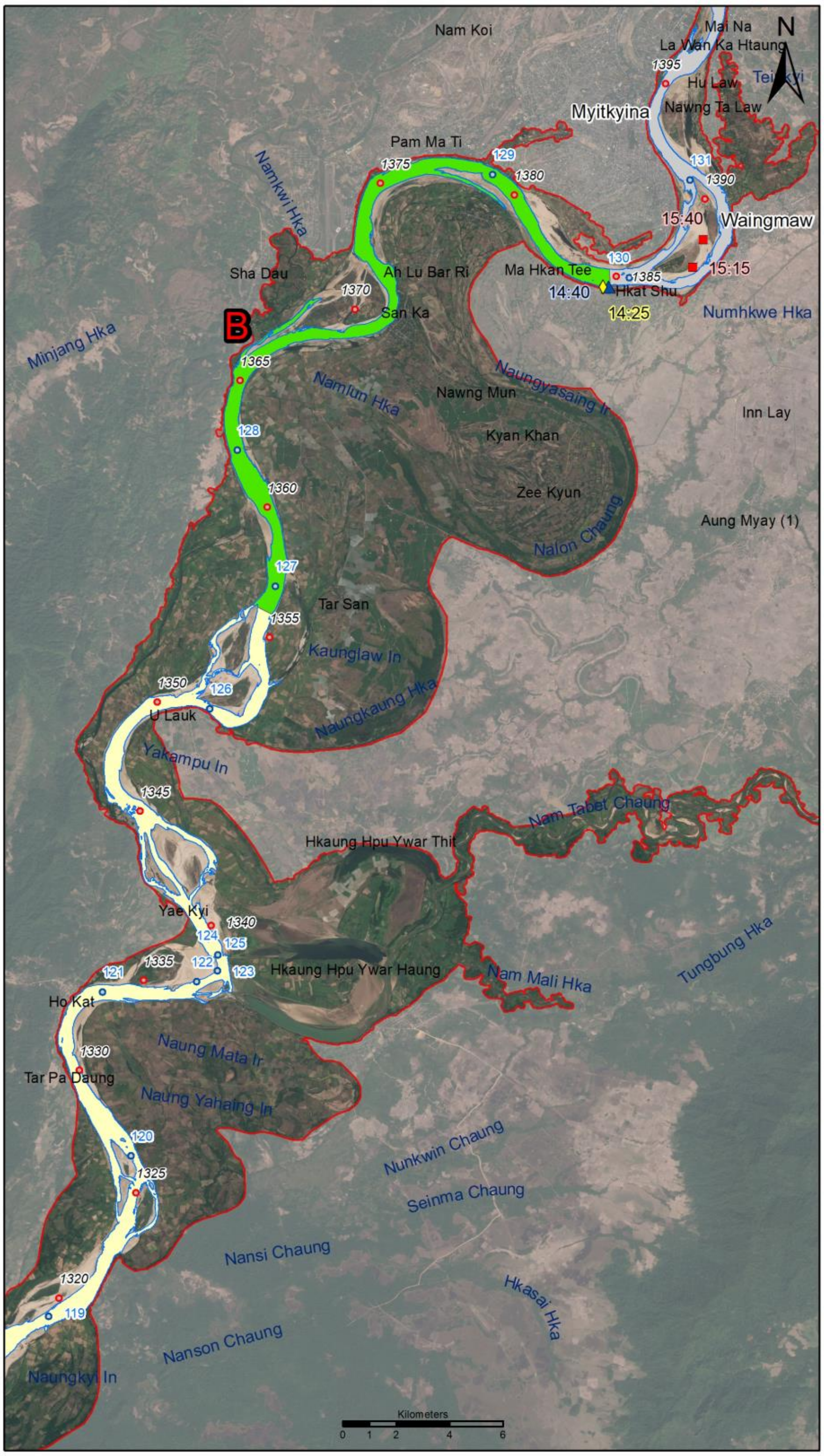
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017



Legend
Samples (time)

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- TSS
- Channel elevation (m)
- Distance from Yangon (5 km)
- Floodplain

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Fluvial pattern

- Anabranching
- Braiding
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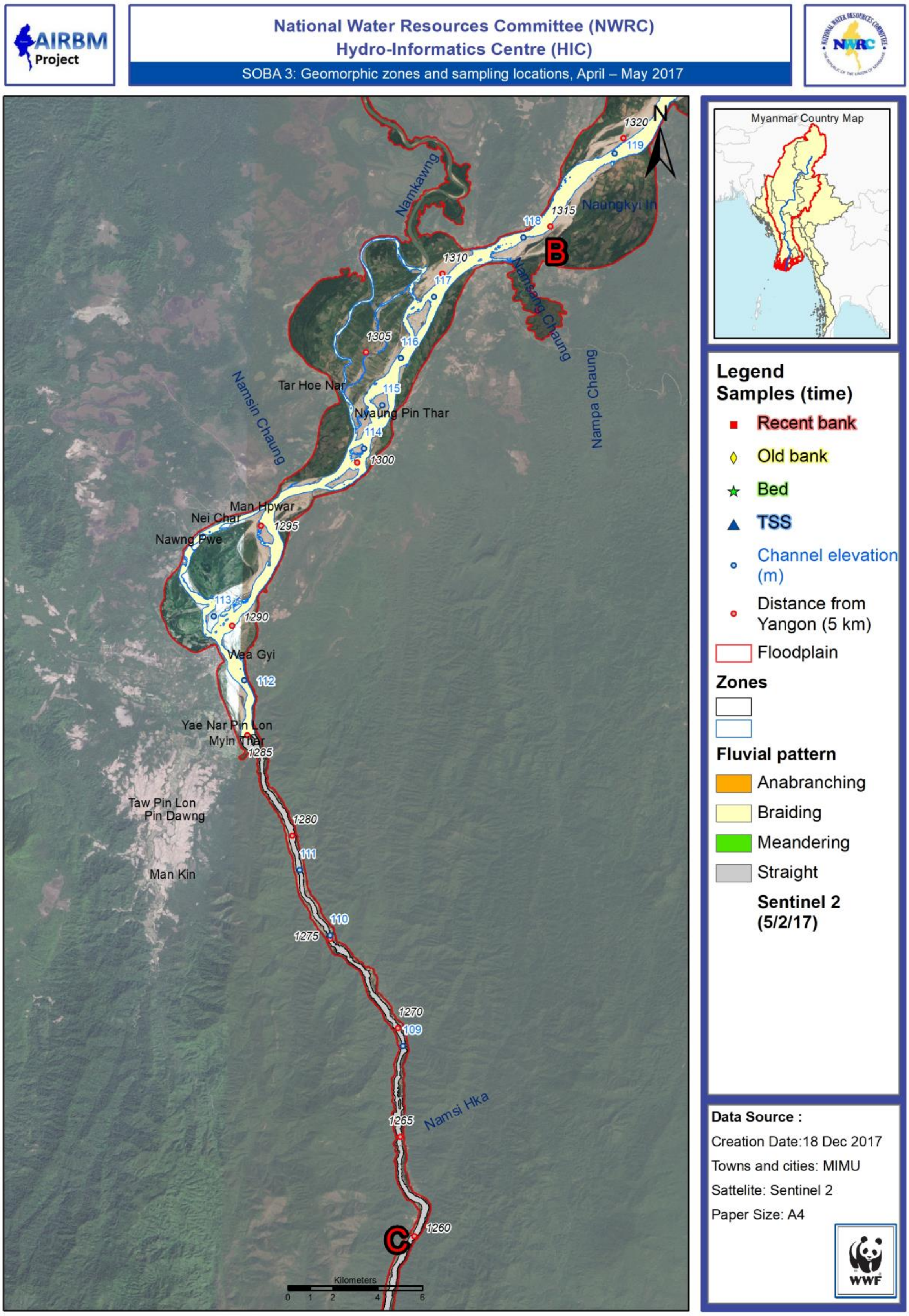
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Floodplain
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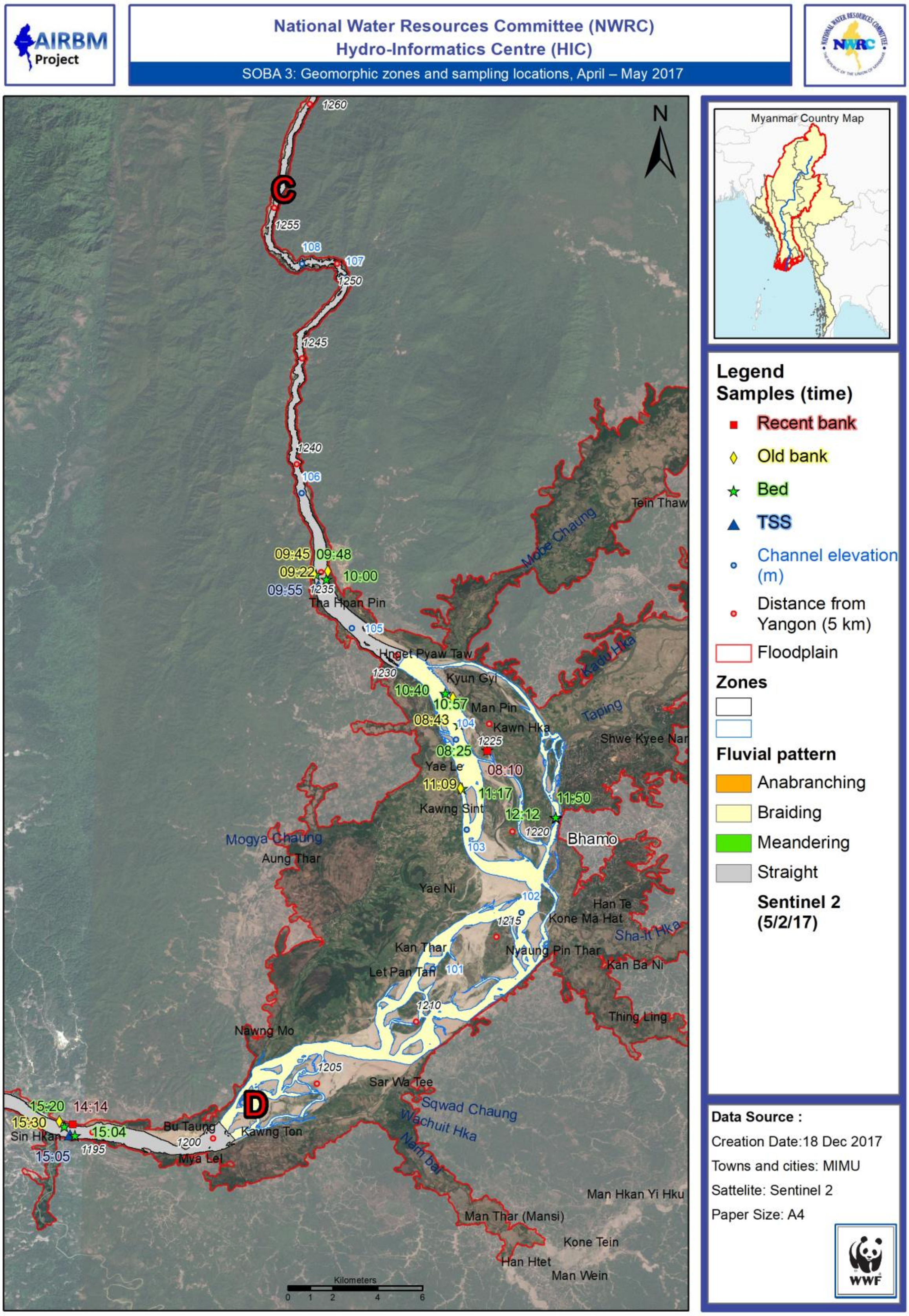
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Kone Ma Hat
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Tein Thaw
Mobe Chaung
Kadu Hka
Taping
Shwe Kyee Nar
Sha-lt Hka
Man Hkan Yi Hku
Man Thar (Mansi)
Kone Tein
Han Htet
Man Wein
Kilometers
0 1 2 4 6
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
Sentinel 2 (5/2/17)
Data Source :
Creation Date:18 Dec 2017
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Sattelite: Sentinel 2
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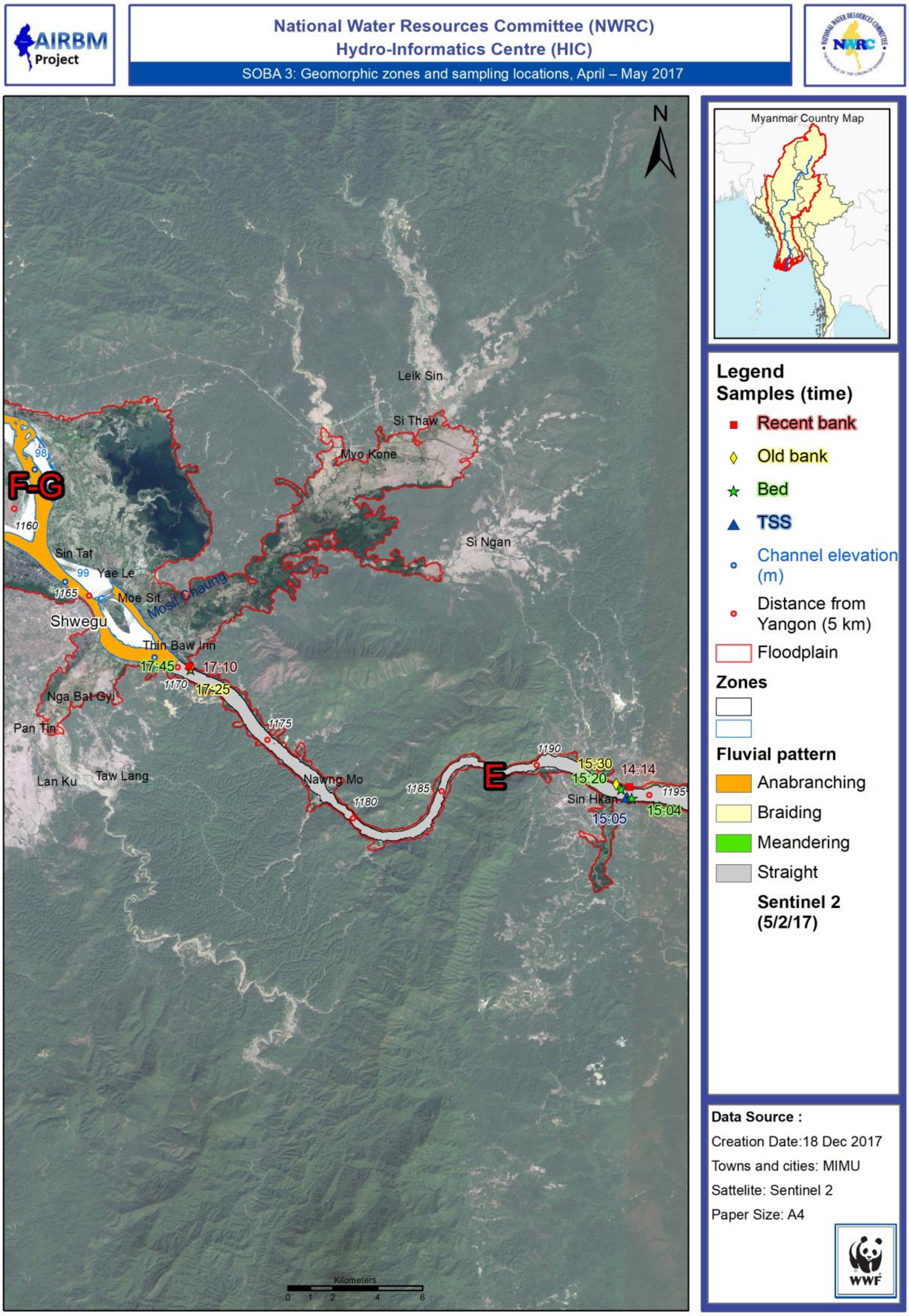
AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
N
Leik Sin
Si Thaw
Myo Kone
Si Ngan
F-G
E
Sin Tat
Yae Le
Moe Sit
Mosit Chaung
Shwegu
Thin Baw Inn
Nga Bat Gyi
Pan Tin
Lan Ku
Taw Lang
Nawng Mo
Sin Hkan
98
99
1160
1165
1170
1175
1180
1185
1190
1195
17:45
17:10
17:25
15:30
14:14
15:20
15:05
15:04
Kilometers
0 1 2 4 6
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
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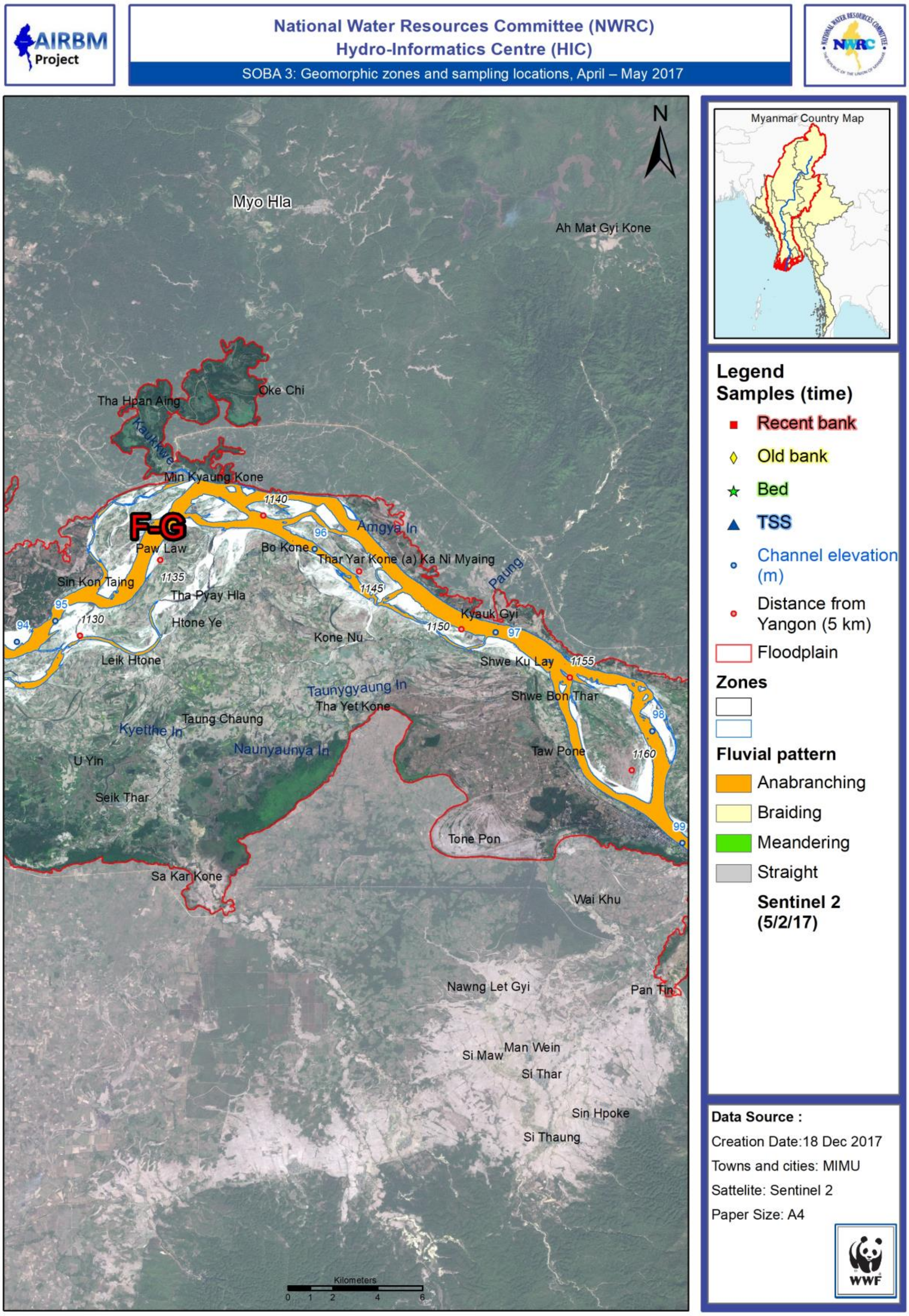
AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
N
Myo Hla
Ah Mat Gyi Kone
Tha Hpan Aing
Oke Chi
Kaukkwe
Min Kyaung Kone
1140
F-G
Paw Law
Bo Kone
96
Amgya In
Thar Yar Kone (a)
Ka Ni Myaing
Paung
Sin Kon Taing
1135
Tha Pyay Hla
1145
95
1130
Htone Ye
Kyauk Gyi
94
Kone Nu
1150
97
Leik Htone
Shwe Ku Lay
1155
Taunygyaung In
Tha Yet Kone
Shwe Bon Thar
Taung Chaung
98
KyettHe In
Naunyaunya In
Taw Pone
1160
U Yin
Seik Thar
99
Tone Pon
Sa Kar Kone
Wai Khu
Nawng Let Gyi
Pan Tin
Si Maw
Man Wein
Si Thar
Sin Hpoke
Si Thaung
Kilometers
0 1 2 4 6
Myanmar Country Map
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Old bank
Bed
TSS
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Zones
Fluvial pattern
Anabranching
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Meandering
Straight
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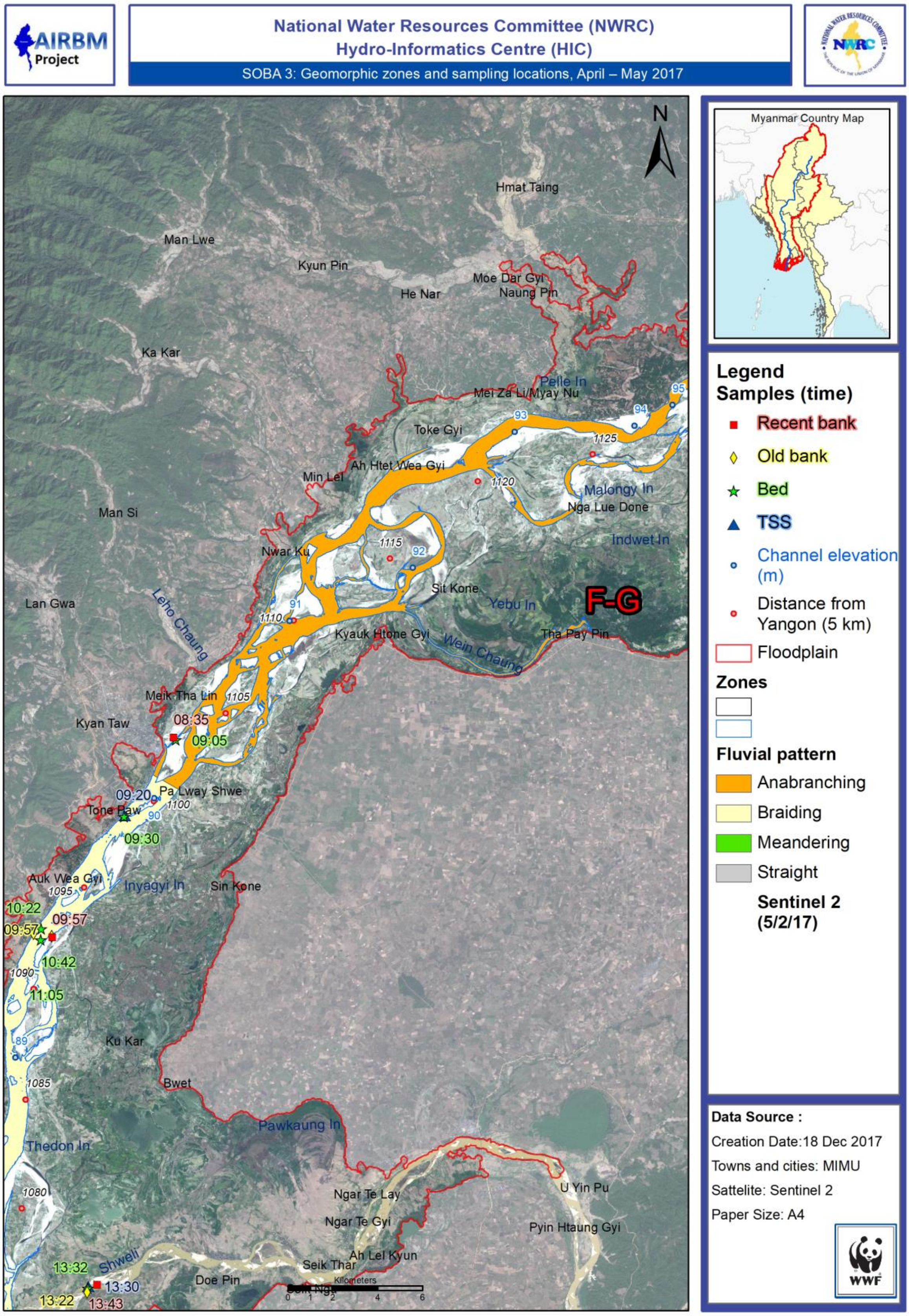
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Old bank
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Anabranching
Braiding
Meandering
Straight
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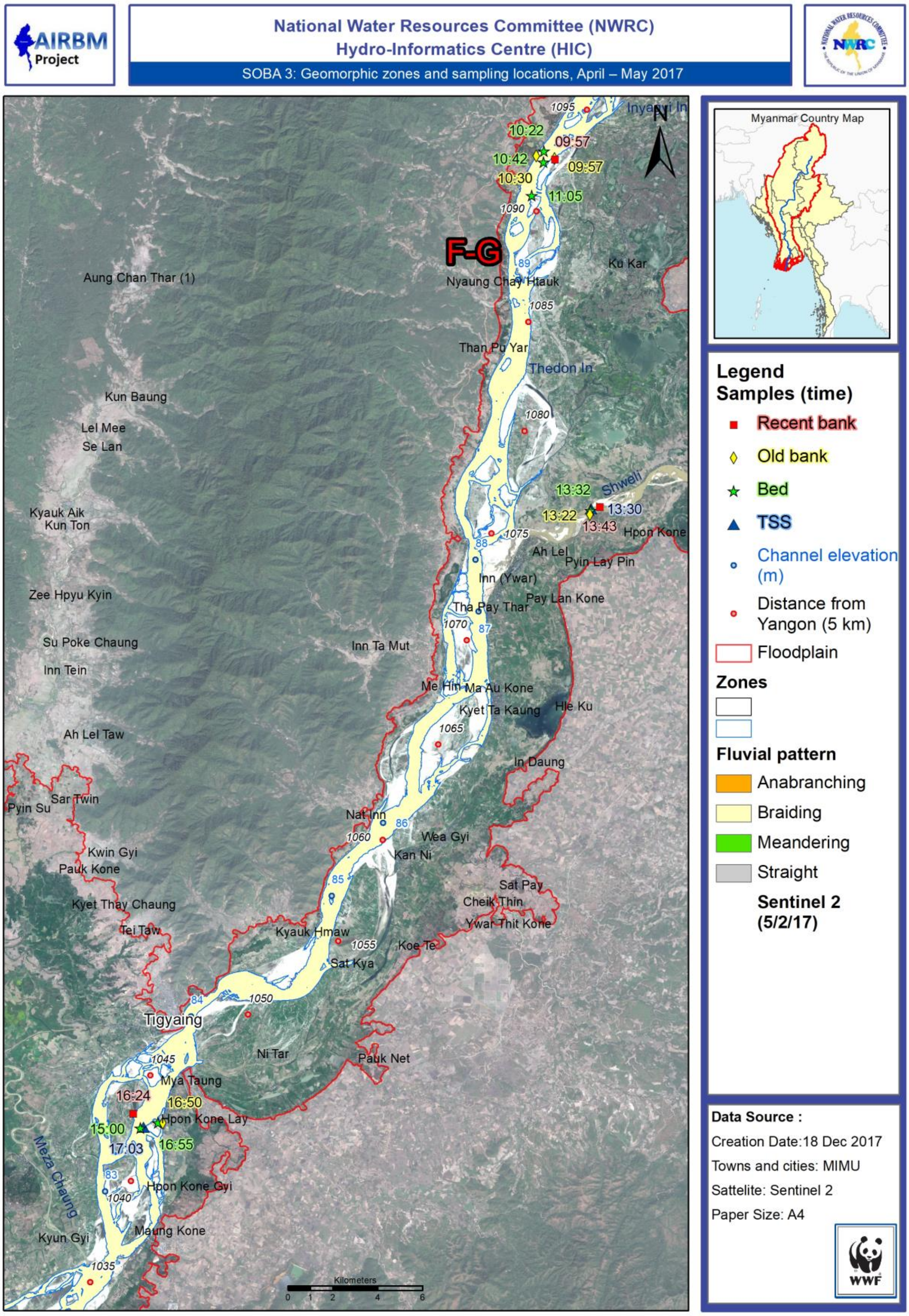
WWF
F-G
Hmat Taing
Man Lwe
Kyun Pin
He Nar
Moe Dar Gyi
Naung Pin
Ka Kar
Pelle In
Mei Za Li/Myay Nu
Toke Gyi
Ah Htet Wea Gyi
Min Lel
Malongy In
Nga Lue Done
Indwet In
Man Si
Nwar Ku
Sit Kone
Yebu In
Tha Pay Pin
Lan Gwa
Leho Chaung
Kyauk Htone Gyi
Wein Chaung
Meik Tha Lin
Kyan Taw
Pa Lway Shwe
Tone Baw
Auk Wea Gyi
Inyagyi In
Sin Kone
Ku Kar
Bwet
Pawkaung In
Thedon In
U Yin Pu
Ngar Te Lay
Ngar Te Gyi
Pyin Htaung Gyi
Ah Lel Kyun
Seik Thar
Doe Pin
Shweli
Kilometers
0 1 2 4 6


AIRBM Project
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F-G
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Old bank
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Zones
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Braiding
Meandering
Straight
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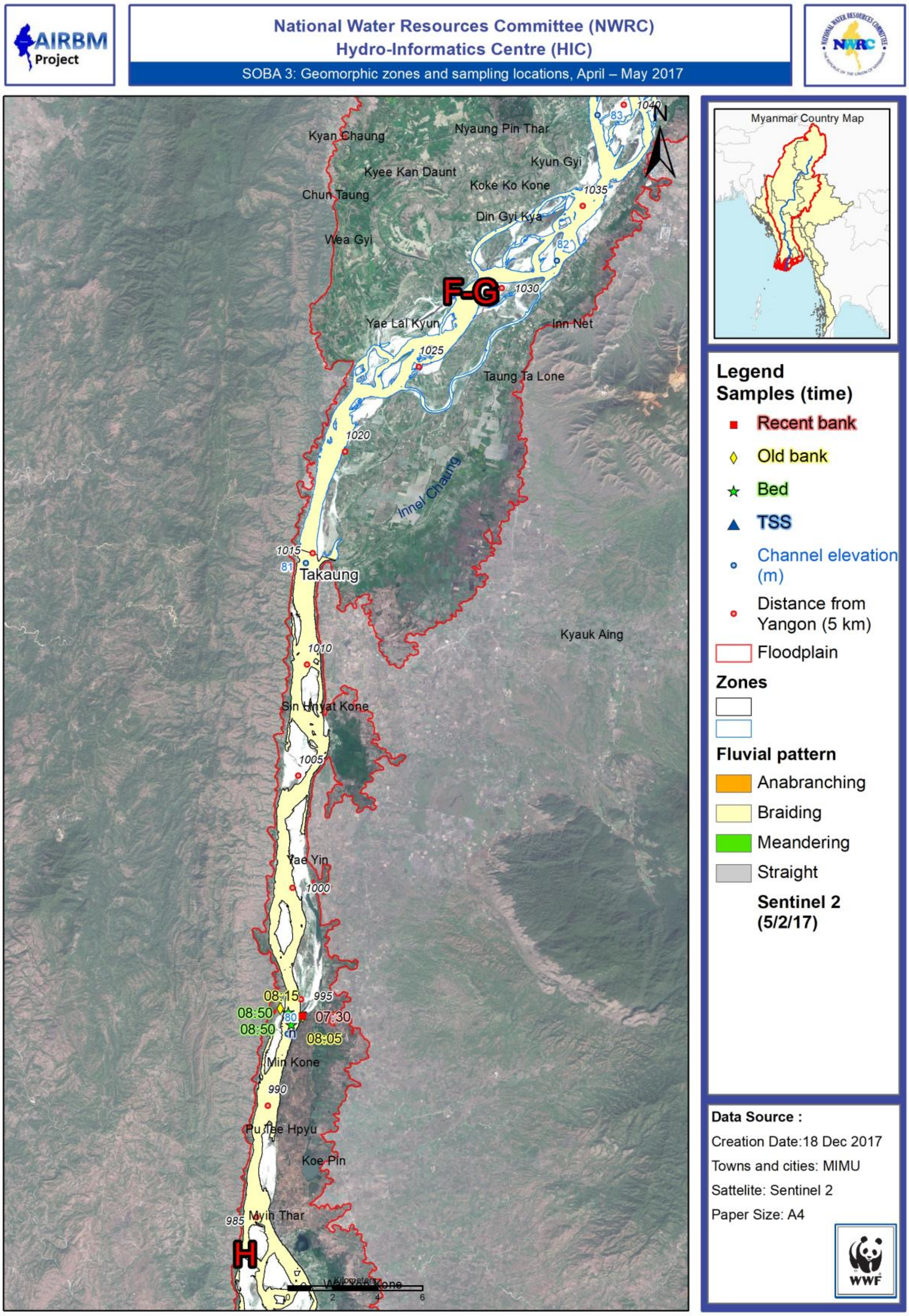
Paper Size: A4
WWF
Kilometers
0 1 2 4 6
Inyagyi In
Thedon In
Shweli
Meza Chaung
Tigyaing
Nyaung Chay Htauk
Than Pu Yar
Ku Kar
Aung Chan Thar (1)
Kun Baung
Lel Mee
Se Lan
Kyauk Aik Kun Ton
Zee Hpyu Kyin
Su Poke Chaung
Inn Tein
Ah Lel Taw
Inn Ta Mut
Hpon Kone
Ah Lel
Pyin Lay Pin
Inn (Ywar)
Tha Pay Thar
Pay Lan Kone
Me Hin
Ma Au Kone
Kyet Ta Kaung
Hle Ku
In Daung
Pyin Su
Sar Twin
Kwin Gyi
Pauk Kone
Kyet Thay Chaung
Tei Taw
Nat Inn
Wea Gyi
Kan Ni
Sat Pay
Cheik Thin
Ywar Thit Kone
Kyauk Hmaw
Koe Te
Sat Kya
Ni Tar
Pauk Net
Mya Taung
Hpon Kone Lay
Hpon Kone Gyi
Maung Kone
Kyun Gyi
10:22
09:57
10:42
09:57
10:30
11:05
13:32
13:30
13:22
13:43
16:24
16:50
15:00
17:03
16:55
1095
1090
1085
1080
1075
1070
1065
1060
1055
1050
1045
1040
1035
89
88
87
86
85
84
83



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SOBA 3: Geomorphic zones and sampling locations, April – May 2017
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
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Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
Sentinel 2 (5/2/17)
Data Source :
Creation Date:18 Dec 2017
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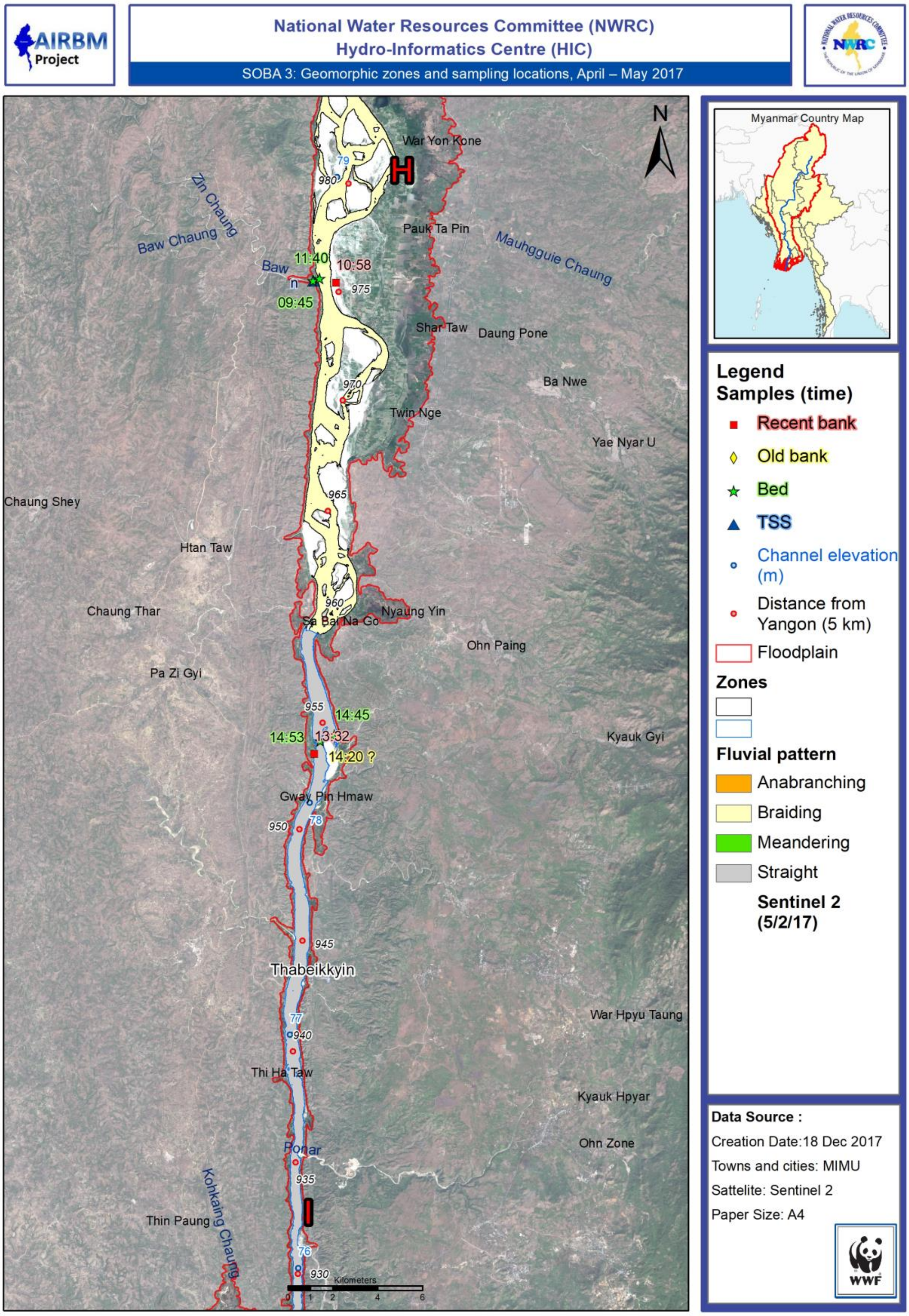
Sattelite: Sentinel 2
Paper Size: A4
F-G
H
Kyan Chaung
Nyaung Pin Thar
Kyee Kan Daunt
Kyun Gyi
Chun Taung
Koke Ko Kone
Din Gyi Kya
Wea Gyi
Yae Lal Kyun
Inn Net
Taung Ta Lone
Innel Chaung
Takaung
Kyauk Aing
Sin Hnyat Kone
Yae Yin
Min Kone
Pu Tee Hpyu
Koe Pin
Myin Thar
08:15
08:50
08:50
07:30
08:05
1040
1035
1030
1025
1020
1015
1010
1005
1000
995
990
985
83
82
81
80


AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
N
War Yon Kone
H
Pauk Ta Pin
Baw Chaung
Zin Chaung
Mauhgguie Chaung
11:40
10:58
09:45
Shar Taw
Daung Pone
Ba Nwe
Twin Nge
Yae Nyar U
Chaung Shey
Htan Taw
Chaung Thar
Nyaung Yin
Sa Bai Na Go
Ohn Paing
Pa Zi Gyi
14:45
14:53
13:32
14:20 ?
Kyauk Gyi
Gway Pin Hmaw
Thabeikkyin
War Hpyu Taung
Thi Ha Taw
Kyauk Hpyar
Ohn Zone
Ponar
Kohkaing Chaung
Thin Paung
I
Kilometers
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
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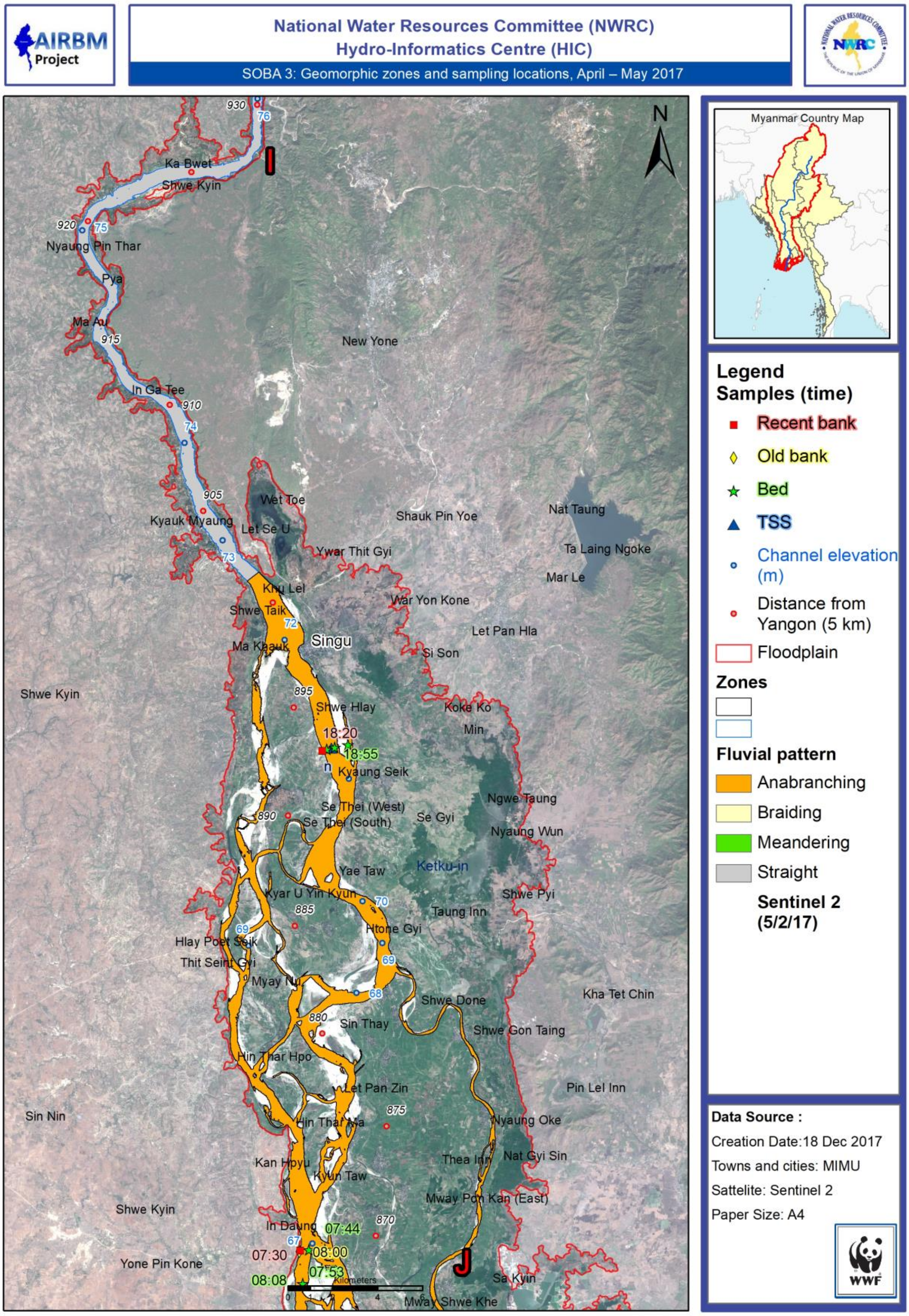
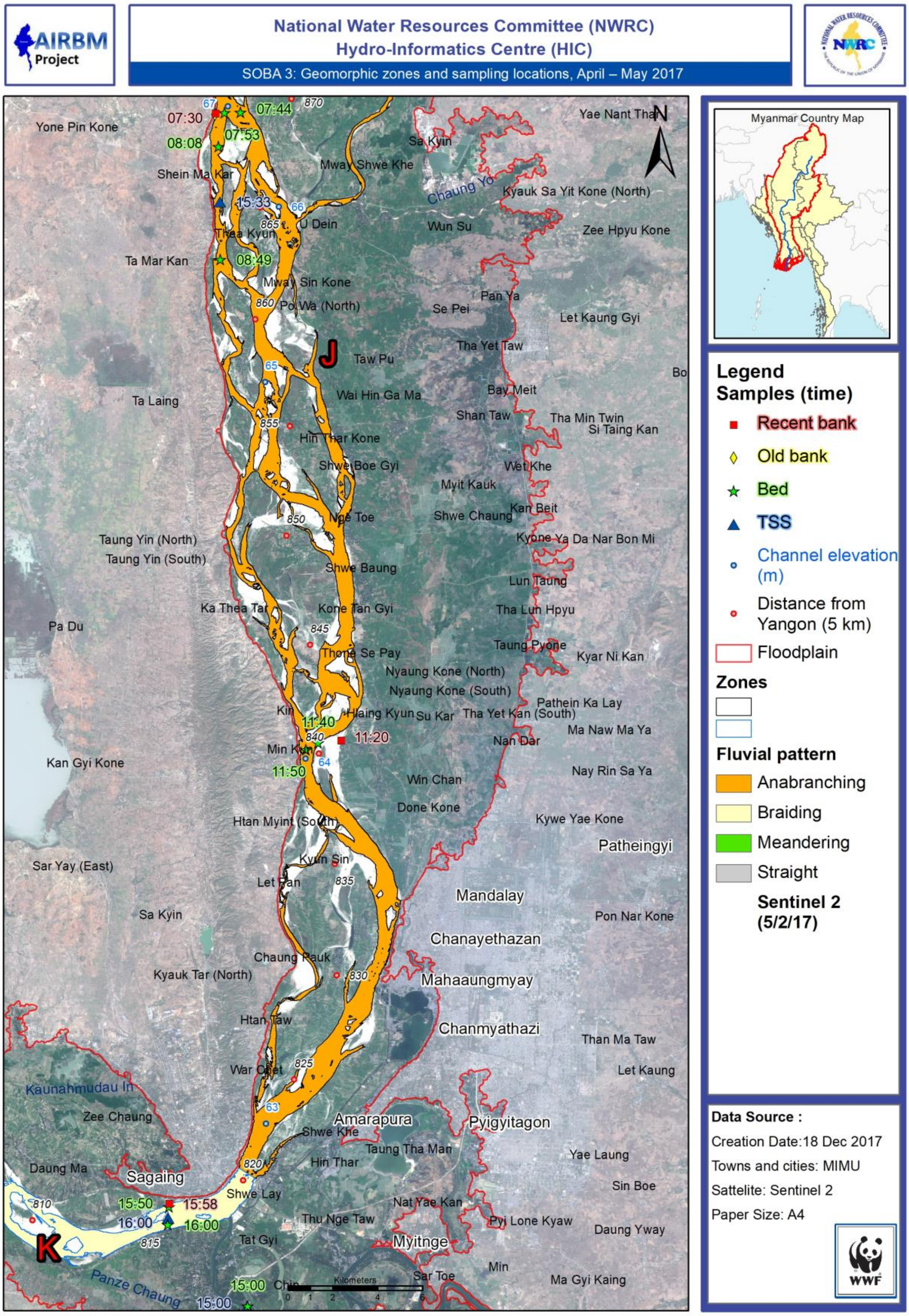

AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
N
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
Sentinel 2 (5/2/17)
Data Source :
Creation Date:18 Dec 2017
Towns and cities: MIMU
Sattelite: Sentinel 2
Paper Size: A4
WWF
I
J
Ka Bwet
Shwe Kyin
Nyaung Pin Thar
Pya
Ma Au
New Yone
In Ga Tee
Wet Toe
Let Se U
Kyauk Myaung
Shauk Pin Yoe
Nat Taung
Ta Laing Ngoke
Mar Le
Ywar Thit Gyi
Khu Lel
Shwe Taik
War Yon Kone
Singu
Ma Khauk
Let Pan Hla
Si Son
Shwe Kyin
Shwe Hlay
Koke Ko
Min
18:20
18:55
Kyaung Seik
Ngwe Taung
Se Thei (West)
Se Thei (South)
Se Gyi
Nyaung Wun
Yae Taw
Ketku-in
Kyar U Yin Kyun
Shwe Pyi
Taung Inn
Htone Gyi
Hlay Poet Seik
Thit Seint Gyi
Myay Nu
Kha Tet Chin
Shwe Done
Sin Thay
Shwe Gon Taing
Hin Thar Hpo
Let Pan Zin
Pin Lel Inn
Sin Nin
Hin Thar Ma
Nyaung Oke
Kan Hpyu
Thea Inn
Nat Gyi Sin
Kyun Taw
Mway Pon Kan (East)
Shwe Kyin
In Daung
07:44
07:30
08:00
07:53
08:08
Yone Pin Kone
Sa Kyin
Mway Shwe Khe
Kilometers
930
920
915
910
905
895
890
885
880
875
870
76
75
74
73
72
70
69
68
67

291



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National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
Sentinel 2 (5/2/17)
Data Source :
Creation Date:18 Dec 2017
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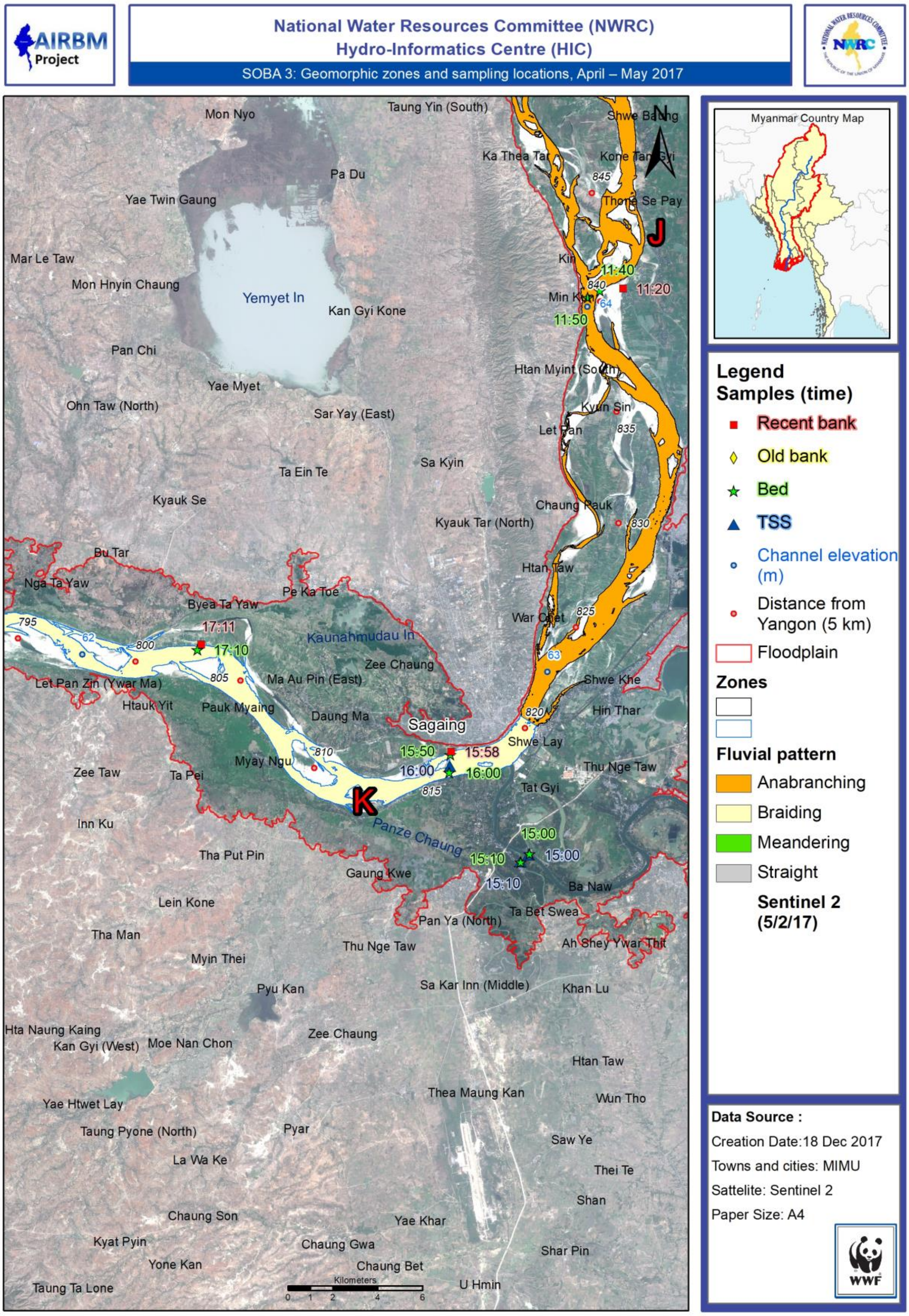
WWF
J
K
Mandalay
Sagaing
Amarapura
Chanayethazan
Mahaaungmyay
Chanmyathazi
Pyigyitagon
Patheingyi
Myitnge
Kilometers


AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
Sentinel 2 (5/2/17)
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Towns and cities: MIMU
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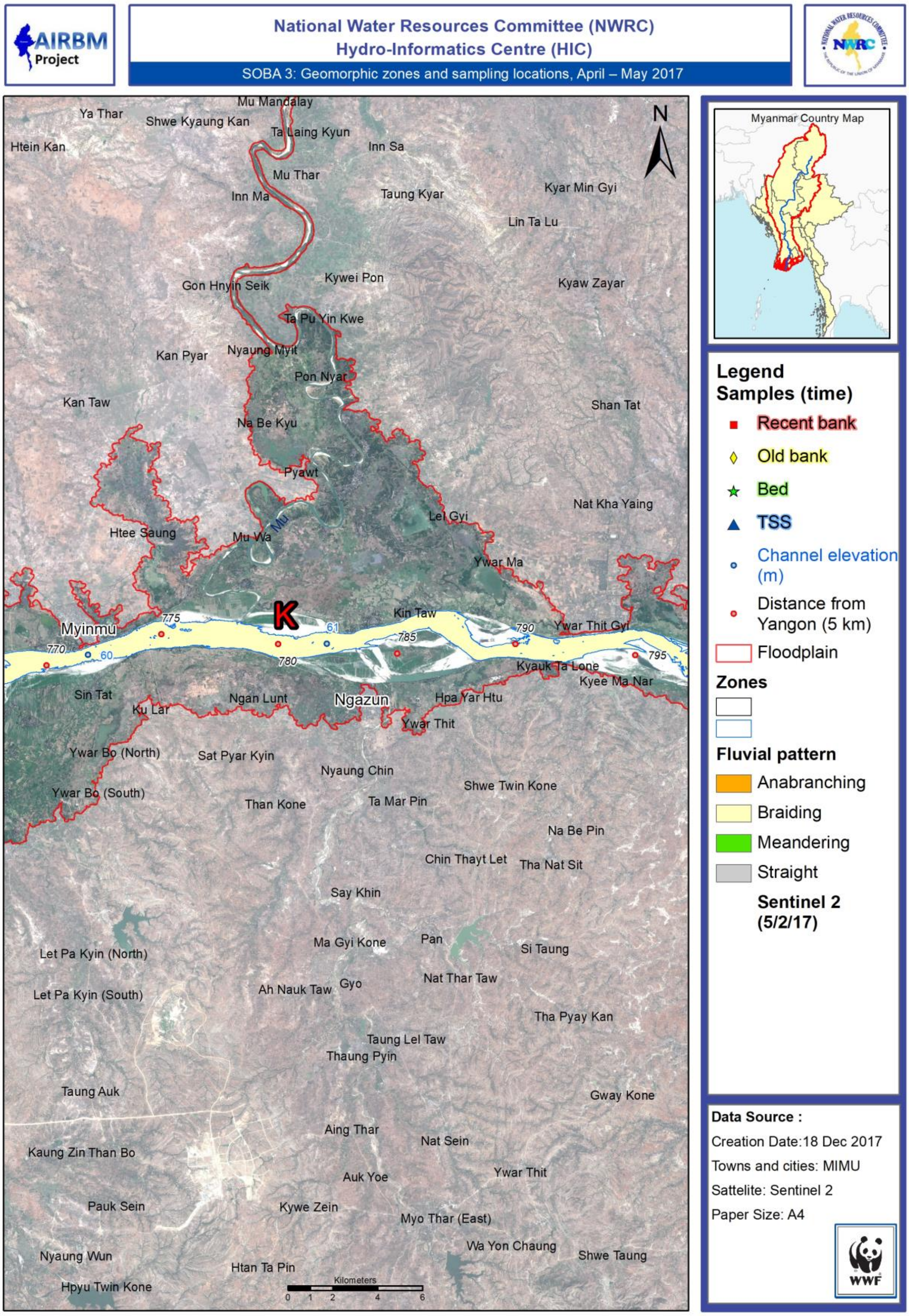
Yemyet In
Sagaing
Kaunghmudau In
Panze Chaung
J
K
Kilometers
0 1 2 4 6


AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
NWRC
N
Mu Mandalay
Ya Thar
Shwe Kyaung Kan
Ta Laing Kyun
Htein Kan
Inn Sa
Mu Thar
Inn Ma
Taung Kyar
Kyar Min Gyi
Lin Ta Lu
Gon Hnyin Seik
Kywei Pon
Kyaw Zayar
Ta Pu Yin Kwe
Kan Pyar
Nyaung Myit
Pon Nyar
Kan Taw
Na Be Kyu
Shan Tat
Pyawt
Nat Kha Yaing
Lel Gyi
Htee Saung
Mu Wa
Mu
Ywar Ma
K
Kin Taw
Myinmu
775
770
60
61
785
780
790
795
Ywar Thit Gyi
Kyauk Ta Lone
Kyee Ma Nar
Sin Tat
Ku Lar
Ngan Lunt
Ngazun
Hpa Yar Htu
Ywar Thit
Ywar Bo (North)
Sat Pyar Kyin
Nyaung Chin
Ywar Bo (South)
Than Kone
Ta Mar Pin
Shwe Twin Kone
Na Be Pin
Chin Thayt Let
Tha Nat Sit
Say Khin
Let Pa Kyin (North)
Ma Gyi Kone
Pan
Si Taung
Let Pa Kyin (South)
Ah Nauk Taw
Gyo
Nat Thar Taw
Tha Pyay Kan
Taung Lel Taw
Thaung Pyin
Taung Auk
Gway Kone
Aing Thar
Kaung Zin Than Bo
Nat Sein
Auk Yoe
Ywar Thit
Pauk Sein
Kywe Zein
Myo Thar (East)
Wa Yon Chaung
Nyaung Wun
Shwe Taung
Htan Ta Pin
Hpyu Twin Kone
Kilometers
0 1 2 4 6
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
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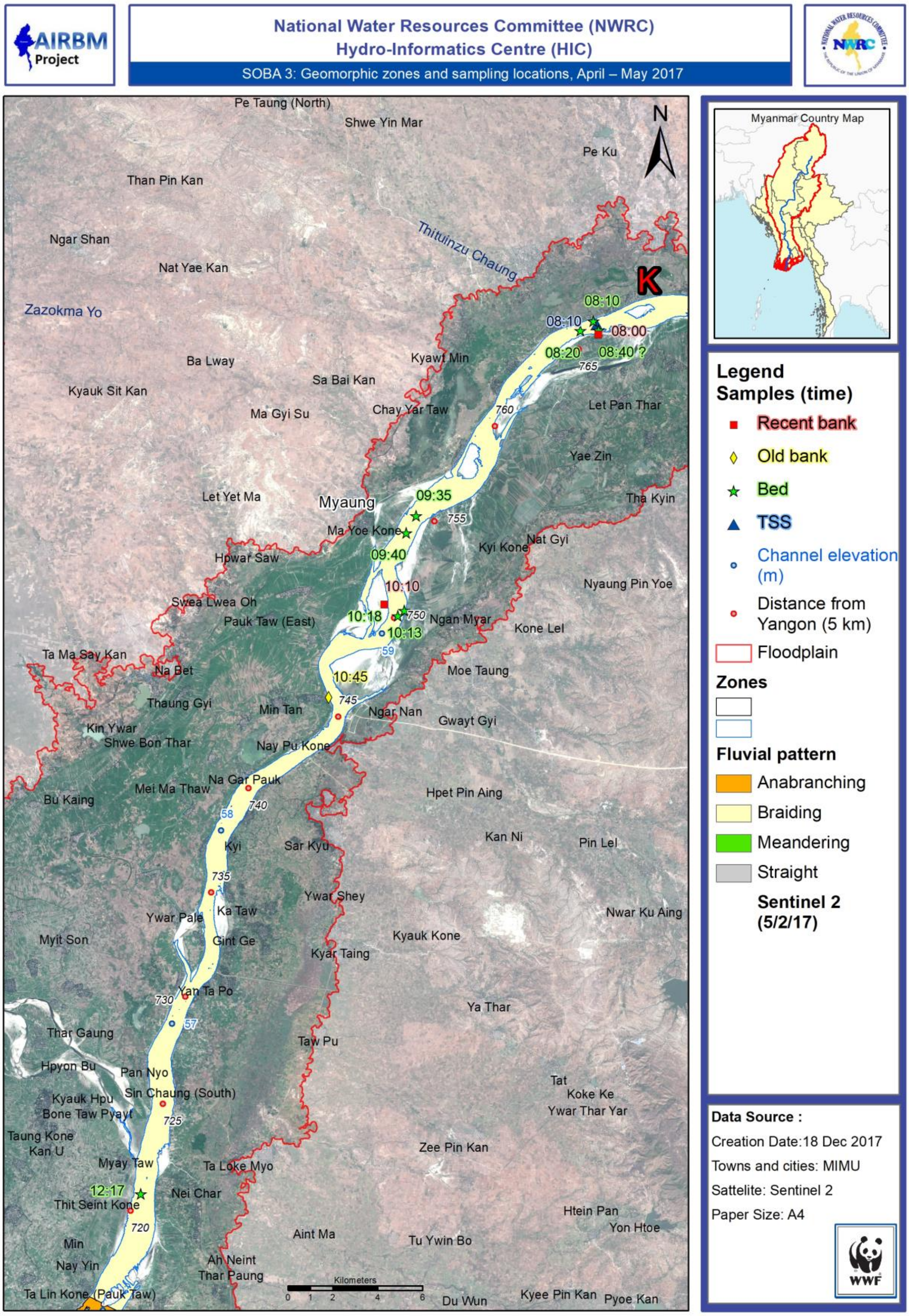
AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
N
K
Pe Taung (North)
Shwe Yin Mar
Pe Ku
Than Pin Kan
Thituinzu Chaung
Ngar Shan
Nat Yae Kan
Zazokma Yo
08:10
08:10
08:00
08:20
08:40 ?
765
Kyawt Min
Ba Lway
Sa Bai Kan
Kyauk Sit Kan
Ma Gyi Su
Chay Yar Taw
760
Let Pan Thar
Yae Zin
Let Yet Ma
Myaung
09:35
Tha Kyin
755
Ma Yoe Kone
Kyi Kone
Nat Gyi
Hpwar Saw
09:40
10:10
Nyaung Pin Yoe
Swea Lwea Oh
10:18
750
Ngan Myar
Pauk Taw (East)
10:13
Kone Lel
59
Ta Ma Say Kan
Na Bet
10:45
Moe Taung
745
Thaung Gyi
Min Tan
Ngar Nan
Gwayt Gyi
Kin Ywar
Shwe Bon Thar
Nay Pu Kone
Na Gar Pauk
Mei Ma Thaw
Bu Kaing
740
Hpet Pin Aing
58
Kyi
Sar Kyu
Kan Ni
Pin Lel
735
Ywar Shey
Ywar Pale
Ka Taw
Nwar Ku Aing
Myit Son
Gint Ge
Kyauk Kone
Kyar Taing
Yan Ta Po
730
57
Ya Thar
Thar Gaung
Taw Pu
Hpyon Bu
Pan Nyo
Sin Chaung (South)
Tat
Kyauk Hpu
Koke Ke
Bone Taw Pyayt
Ywar Thar Yar
725
Taung Kone
Kan U
Zee Pin Kan
Myay Taw
Ta Loke Myo
12:17
Nei Char
Thit Seint Kone
Htein Pan
720
Yon Htoe
Min
Aint Ma
Tu Ywin Bo
Nay Yin
Ah Neint
Thar Paung
Kilometers
0 1 2 4 6
Ta Lin Kone (Pauk Taw)
Du Wun
Kyee Pin Kan
Pyoe Kan
Myanmar Country Map
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Old bank
Bed
TSS
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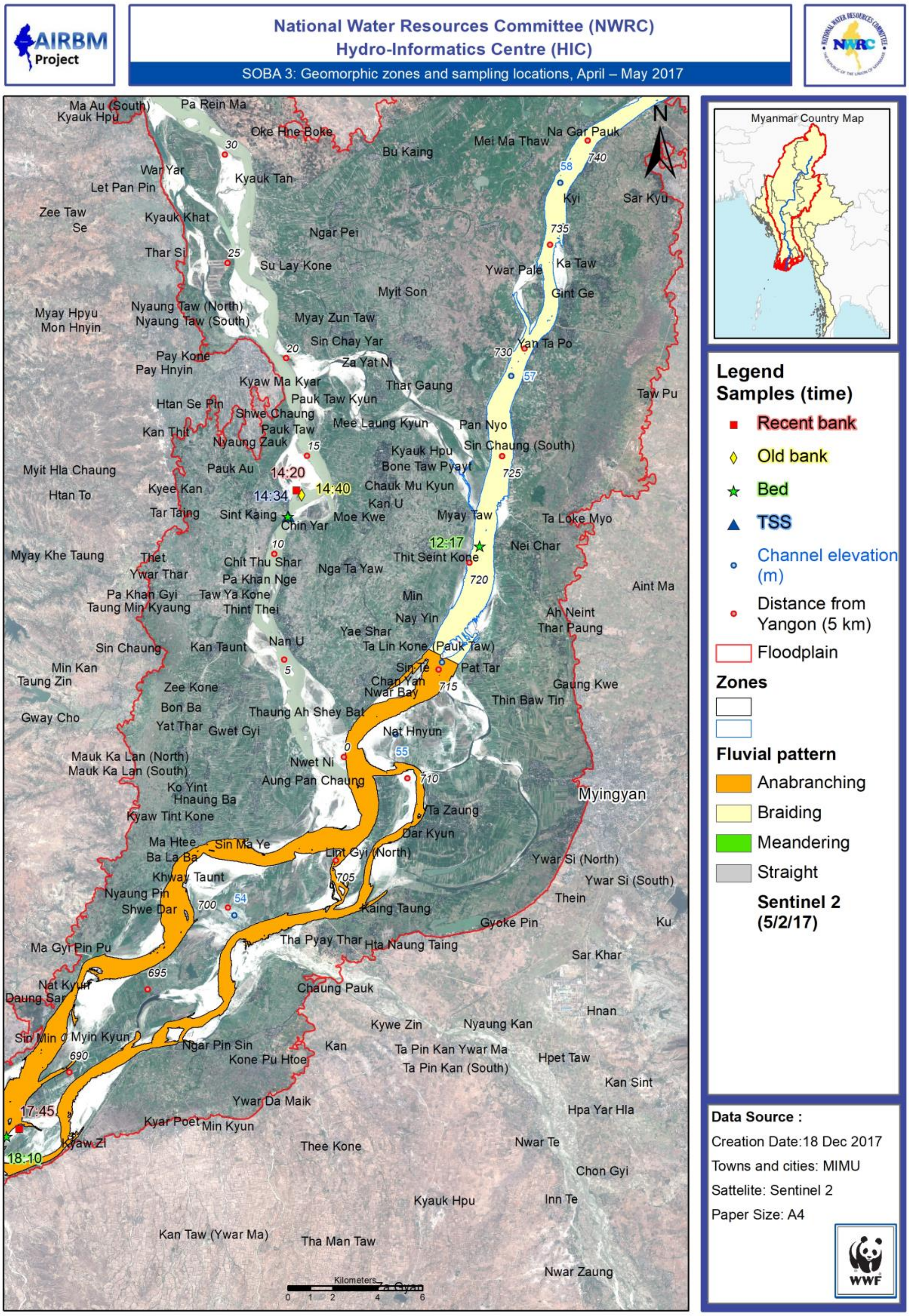
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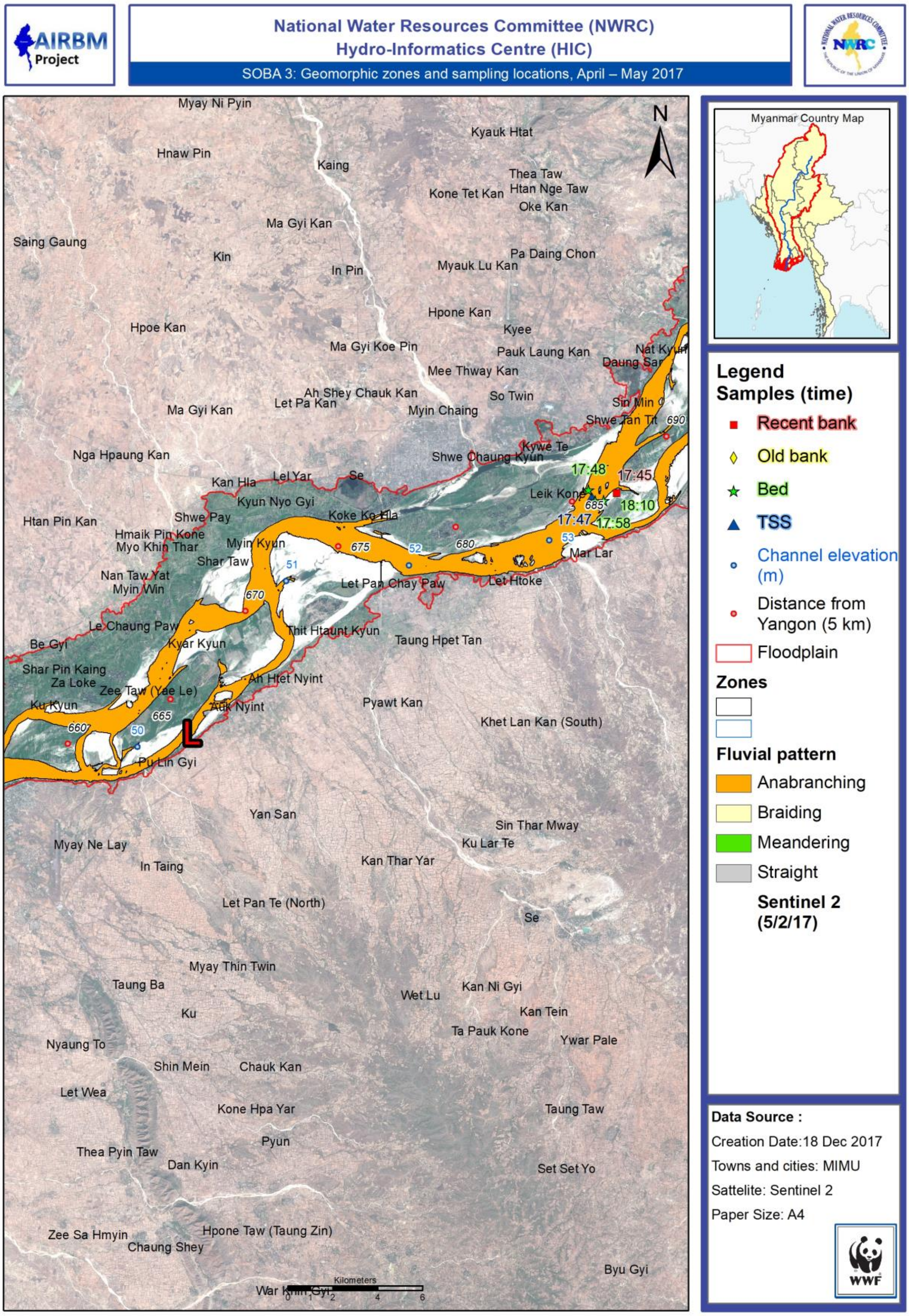
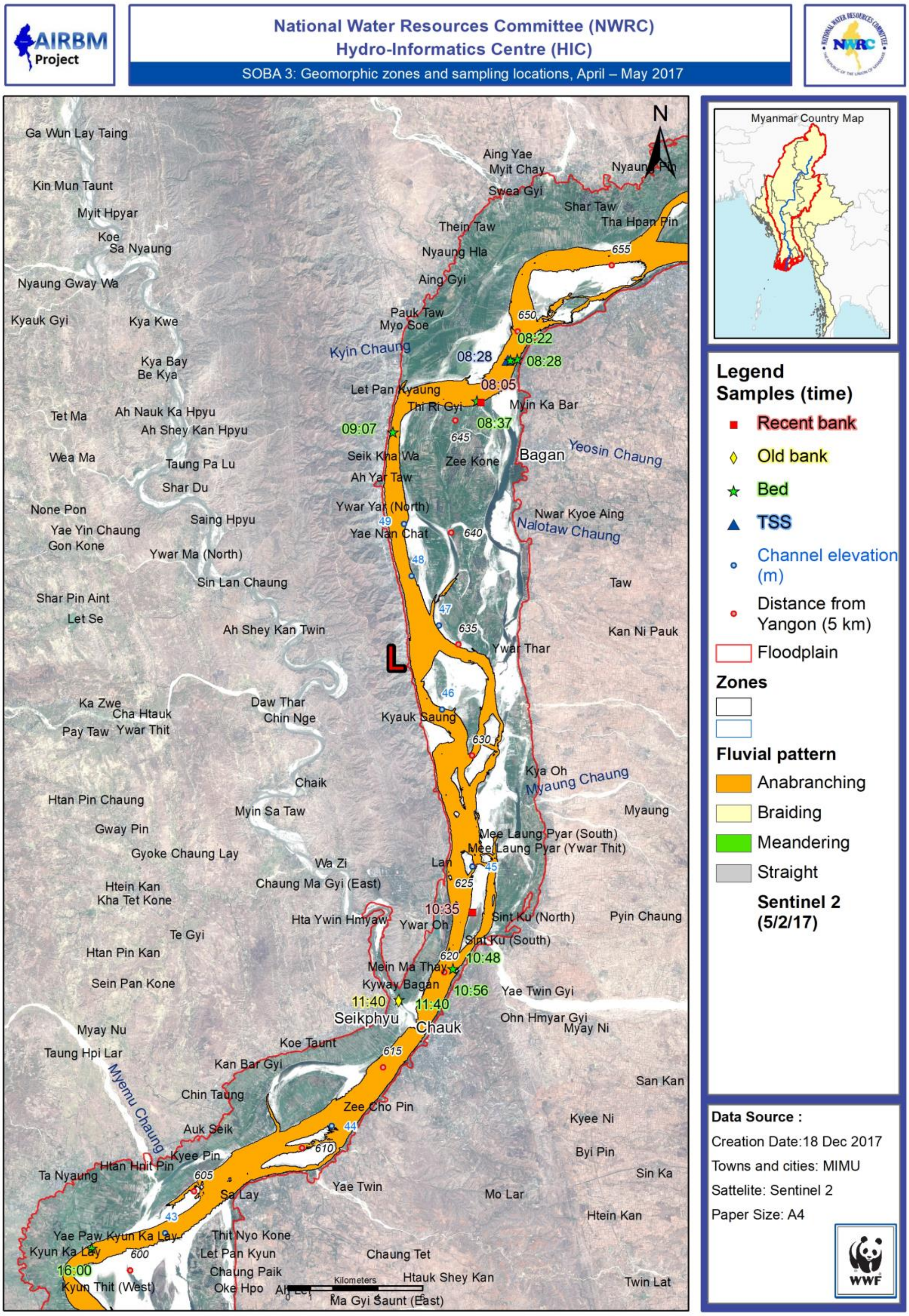
Kilometers
0 1 2 4 6
N
14:20
14:34
14:40
12:17
17:45
18:10
Myingyan
Ma Au (South)
Kyauk Hpu
Pa Rein Ma
Oke Hne Boke
Bu Kaing
Mei Ma Thaw
Na Gar Pauk
War Yar
Let Pan Pin
Kyauk Tan
Zee Taw Se
Kyauk Khat
Ngar Pei
Thar Si
Su Lay Kone
Ywar Pale
Ka Taw
Gint Ge
Myit Son
Myay Hpyu
Mon Hnyin
Nyaung Taw (North)
Nyaung Taw (South)
Myay Zun Taw
Sin Chay Yar
Pay Kone
Pay Hnyin
Za Yat Ni
Yan Ta Po
Kyaw Ma Kyar
Thar Gaung
Taw Pu
Pauk Taw Kyun
Htan Se Pin
Shwe Chaung
Pauk Taw
Mee Laung Kyun
Pan Nyo
Kan Thit
Nyaung Zauk
Kyauk Hpu
Sin Chaung (South)
Bone Taw Pyayt
Pauk Au
Myit Hla Chaung
Chauk Mu Kyun
Kyee Kan
Htan To
Kan U
Tar Taing
Sint Kaing
Chin Yar
Moe Kwe
Myay Taw
Ta Loke Myo
Nei Char
Myay Khe Taung
Thet
Ywar Thar
Chit Thu Shar
Thit Seint Kone
Nga Ta Yaw
Pa Khan Nge
Pa Khan Gyi
Taw Ya Kone
Aint Ma
Taung Min Kyaung
Thint Thei
Min
Nay Yin
Ah Neint
Thar Paung
Yae Shar
Sin Chaung
Kan Taunt
Nan U
Ta Lin Kone (Pauk Taw)
Min Kan
Taung Zin
Sin Te
Pat Tar
Zee Kone
Chan Yan
Nwar Bay
Gaung Kwe
Bon Ba
Thin Baw Tin
Gway Cho
Yat Thar
Thaung Ah Shey Bat
Gwet Gyi
Nat Hnyun
Mauk Ka Lan (North)
Mauk Ka Lan (South)
Nwet Ni
Aung Pan Chaung
Ko Yint
Hnaung Ba
Kyaw Tint Kone
Ta Zaung
Dar Kyun
Ma Htee
Sin Ma Ye
Ba La Ba
Lint Gyi (North)
Ywar Si (North)
Khway Taunt
Ywar Si (South)
Nyaung Pin
Thein
Shwe Dar
Kaing Taung
Ku
Gyoke Pin
Tha Pyay Thar
Hta Naung Taing
Ma Gyi Pin Pu
Sar Khar
Nat Kyun
Daung Sar
Chaung Pauk
Hnan
Sin Min
Myin Kyun
Kywe Zin
Nyaung Kan
Ngar Pin Sin
Kan
Ta Pin Kan Ywar Ma
Ta Pin Kan (South)
Kone Pu Htoe
Hpet Taw
Kan Sint
Ywar Da Maik
Hpa Yar Hla
Kyar Poet
Min Kyun
Kyaw Zi
Thee Kone
Nwar Te
Chon Gyi
Kyauk Hpu
Inn Te
Kan Taw (Ywar Ma)
Tha Man Taw
Nwar Zaung
Za Gyan


AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
N
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
Sentinel 2 (5/2/17)
Data Source :
Creation Date:18 Dec 2017
Towns and cities: MIMU
Sattelite: Sentinel 2
Paper Size: A4
WWF
Myay Ni Pyin
Kyauk Htat
Hnaw Pin
Kaing
Thea Taw
Htan Nge Taw
Kone Tet Kan
Oke Kan
Ma Gyi Kan
Saing Gaung
Kin
In Pin
Pa Daing Chon
Myauk Lu Kan
Hpone Kan
Hpoe Kan
Kyee
Ma Gyi Koe Pin
Pauk Laung Kan
Mee Thway Kan
Ah Shey Chauk Kan
Let Pa Kan
So Twin
Ma Gyi Kan
Myin Chaing
Shwe Tan Tit
690
Kywe Te
Nga Hpaung Kan
Shwe Chaung Kyun
17:48
17:45
Kan Hla
Lel Yar
Se
Leik Kone
Kyun Nyo Gyi
685
18:10
Htan Pin Kan
Shwe Pay
Koke Ko Hla
17:47
17:58
Hmaik Pin Kone
Myo Khin Thar
Myin Kyun
675
52
680
53
Mar Lar
Shar Taw
51
Nan Taw Yat
Myin Win
Let Pan Chay Paw
Let Htoke
670
Le Chaung Paw
Hit Htaunt Kyun
Taung Hpet Tan
Be Gyi
Kyar Kyun
Shar Pin Kaing
Za Loke
Ah Htet Nyint
Zee Taw (Yae Le)
Pyawt Kan
Ku Kyun
Auk Nyint
665
Khet Lan Kan (South)
660
50
L
Pu Lin Gyi
Yan San
Sin Thar Mway
Ku Lar Te
Myay Ne Lay
In Taing
Kan Thar Yar
Let Pan Te (North)
Se
Myay Thin Twin
Taung Ba
Wet Lu
Kan Ni Gyi
Ku
Kan Tein
Ta Pauk Kone
Ywar Pale
Nyaung To
Shin Mein
Chauk Kan
Let Wea
Kone Hpa Yar
Taung Taw
Pyun
Thea Pyin Taw
Dan Kyin
Set Set Yo
Zee Sa Hmyin
Hpone Taw (Taung Zin)
Chaung Shey
Byu Gyi
Kilometers
0 1 2 4 6

297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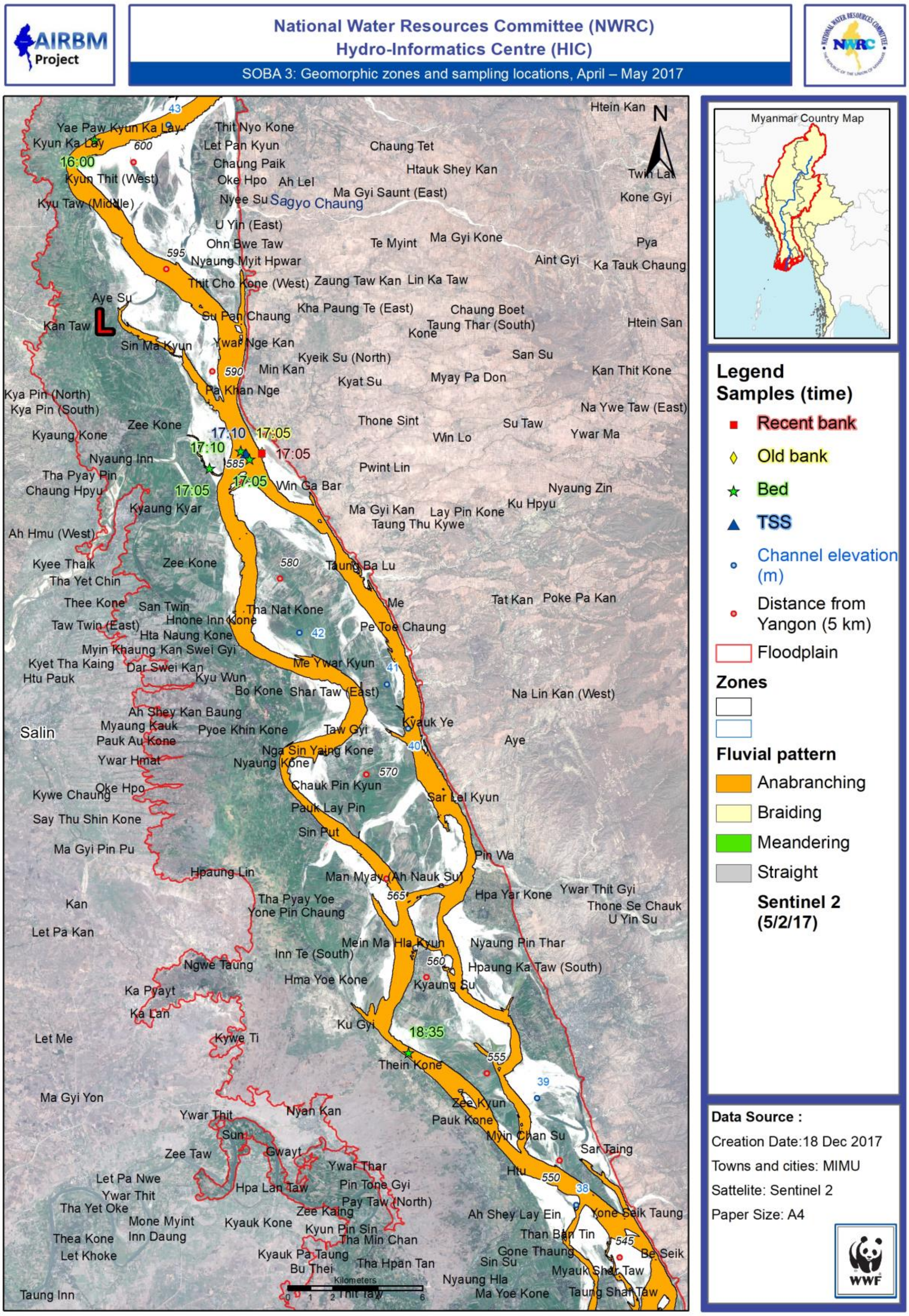
WWF
Kilometers
L
Ga Wun Lay Taing
Kin Mun Taunt
Myit Hpyar
Koe
Sa Nyaung
Nyaung Gway Wa
Kyauk Gyi
Kya Kwe
Kya Bay
Be Kya
Tet Ma
Ah Nauk Ka Hpyu
Ah Shey Kan Hpyu
Wea Ma
Taung Pa Lu
Shar Du
None Pon
Saing Hpyu
Yae Yin Chaung
Gon Kone
Ywar Ma (North)
Sin Lan Chaung
Shar Pin Aint
Let Se
Ah Shey Kan Twin
Ka Zwe
Cha Htauk
Pay Taw
Ywar Thit
Daw Thar
Chin Nge
Chaik
Htan Pin Chaung
Gway Pin
Myin Sa Taw
Gyoke Chaung Lay
Wa Zi
Htein Kan
Kha Tet Kone
Chaung Ma Gyi (East)
Hta Ywin Hmyaw
Te Gyi
Htan Pin Kan
Sein Pan Kone
Myay Nu
Taung Hpi Lar
Myemu Chaung
Koe Taunt
Kan Bar Gyi
Chin Taung
Auk Seik
Kyee Pin
Htan Hnit Pin
Ta Nyaung
Sa Lay
Yae Paw Kyun Ka Lay
Kyun Ka Lay
Kyun Thit (West)
Thit Nyo Kone
Let Pan Kyun
Chaung Paik
Oke Hpo
Ma Gyi Saunt (East)
Htauk Shey Kan
Chaung Tet
Yae Twin
Mo Lar
Htein Kan
Twin Lat
Sin Ka
Byi Pin
Kyee Ni
San Kan
Zee Cho Pin
Seikphyu
Chauk
Ohn Hmyar Gyi
Myay Ni
Yae Twin Gyi
Kyway Bagan
Mein Ma Thay
Sint Ku (South)
Sint Ku (North)
Ywar Oh
Pyin Chaung
Lan
Mee Laung Pyar (South)
Mee Laung Pyar (Ywar Thit)
Myaung
Kya Oh
Myaung Chaung
Kyauk Saung
Ywar Thar
Kan Ni Pauk
Taw
Yae Nan Chat
Ywar Yar (North)
Nwar Kyoe Aing
Nalotaw Chaung
Ah Yar Taw
Seik Kha Wa
Zee Kone
Bagan
Yeosin Chaung
Thi Ri Gyi
Myin Ka Bar
Let Pan Kyaung
Kyin Chaung
Pauk Taw
Myo Soe
Aing Gyi
Nyaung Hla
Thein Taw
Aing Yae
Myit Chay
Swea Gyi
Shar Taw
Tha Hpan Pin
Nyaung Pin
655
650
645
640
635
630
625
620
615
610
605
600
49
48
47
46
45
44
43
08:22
08:28
08:28
08:05
08:37
09:07
10:35
10:48
10:56
11:40
11:40
16:00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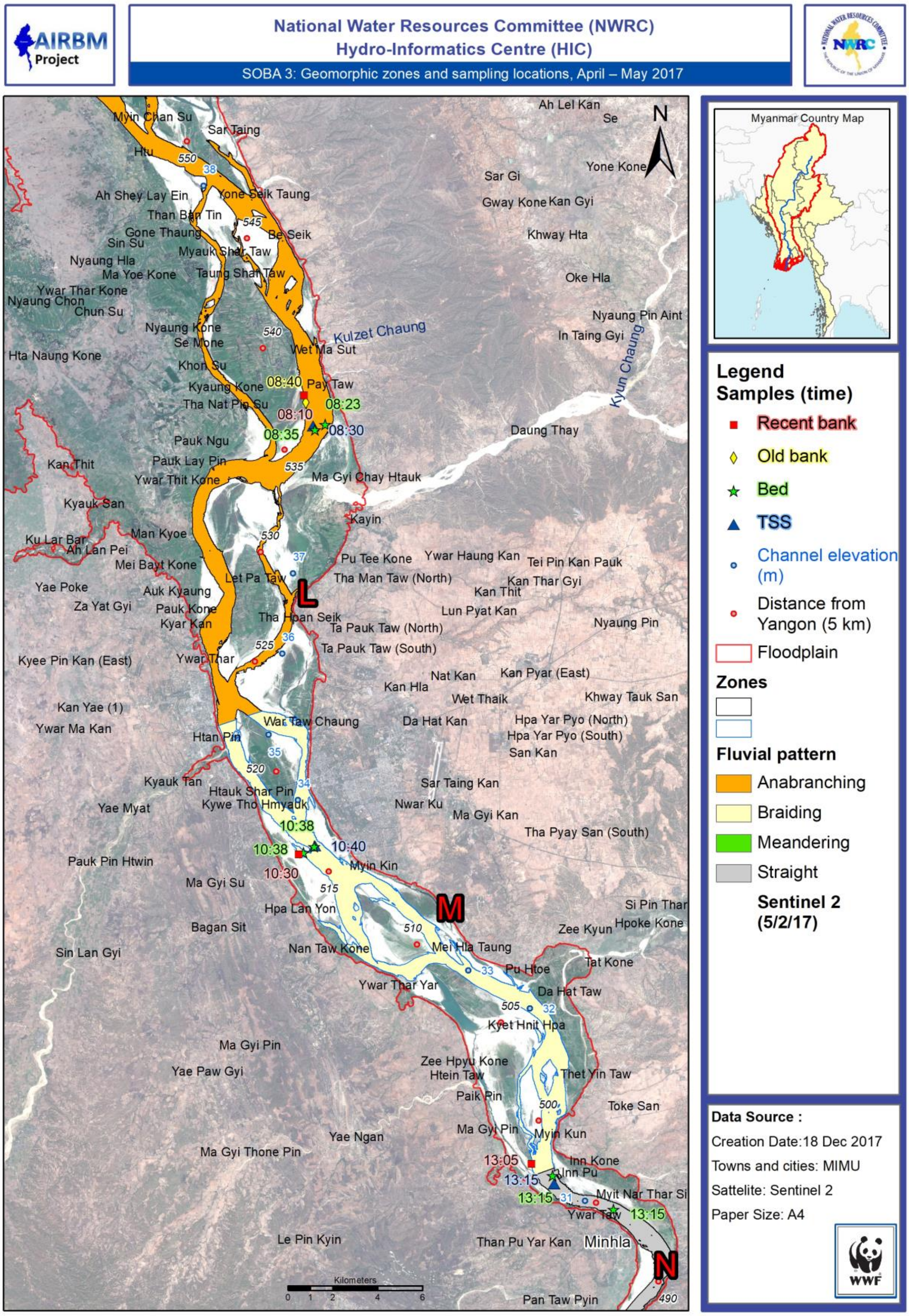
Paper Size: A4
WWF
N
L
Kilometers
0 1 2 4 6
16:00
17:10
17:05
17:10
17:05
17:05
17:05
18:35
600
595
590
585
580
570
565
560
555
550
545
43
42
41
40
39
38
Htein Kan
Yae Paw Kyun Ka Lay
Thit Nyo Kone
Kyun Ka Lay
Let Pan Kyun
Chaung Tet
Chaung Paik
Htauk Shey Kan
Kyun Thit (West)
Oke Hpo
Ah Lel
Twin Lay
Ma Gyi Saunt (East)
Kone Gyi
Kyu Taw (Middle)
Nyee Su
Sagyo Chaung
U Yin (East)
Ohn Bwe Taw
Te Myint
Ma Gyi Kone
Pya
Nyaung Myit Hpwar
Aint Gyi
Ka Tauk Chaung
Thit Cho Kone (West)
Zaung Taw Kan
Lin Ka Taw
Aye Su
Kha Paung Te (East)
Chaung Boet
Su Pan Chaung
Kone
Taung Thar (South)
Htein San
Kan Taw
Sin Ma Kyun
Ywar Nge Kan
Kyeik Su (North)
San Su
Min Kan
Kan Thit Kone
Kyat Su
Myay Pa Don
Pa Khan Nge
Kya Pin (North)
Kya Pin (South)
Na Ywe Taw (East)
Thone Sint
Su Taw
Zee Kone
Kyaung Kone
Win Lo
Ywar Ma
Nyaung Inn
Pwint Lin
Tha Pyay Pin
Win Ga Bar
Nyaung Zin
Chaung Hpyu
Ku Hpyu
Kyaung Kyar
Ma Gyi Kan
Lay Pin Kone
Taung Thu Kywe
Ah Hmu (West)
Kyee Thaik
Zee Kone
Taung Ba Lu
Tha Yet Chin
Tat Kan
Poke Pa Kan
Thee Kone
San Twin
Tha Nat Kone
Me
Hnone Inn Kone
Taw Twin (East)
Pe Toe Chaung
Hta Naung Kone
Myin Khaung Kan Swei Gyi
Kyet Tha Kaing
Dar Swei Kan
Me Ywar Kyun
Htu Pauk
Kyu Wun
Bo Kone
Shar Taw (East)
Na Lin Kan (West)
Ah Shey Kan Baung
Salin
Myaung Kauk
Kyauk Ye
Pyoe Khin Kone
Taw Gyi
Pauk Au Kone
Aye
Nga Sin Yaing Kone
Ywar Hmat
Nyaung Kone
Kywe Chaung
Oke Hpo
Chauk Pin Kyun
Sar Lel Kyun
Pauk Lay Pin
Say Thu Shin Kone
Sin Put
Ma Gyi Pin Pu
Pin Wa
Hpaung Lin
Man Myay (Ah Nauk Su)
Hpa Yar Kone
Ywar Thit Gyi
Tha Pyay Yoe
Thone Se Chauk
Kan
Yone Pin Chaung
U Yin Su
Let Pa Kan
Mein Ma Hla Kyun
Nyaung Pin Thar
Inn Te (South)
Ngwe Taung
Hpaung Ka Taw (South)
Hma Yoe Kone
Kyaung Su
Ka Pyayt
Ka Lan
Ku Gyi
Let Me
Kywe Ti
Thein Kone
Ma Gyi Yon
Zee Kyun
Ywar Thit
Nyan Kan
Pauk Kone
Sun
Myin Chan Su
Sar Taing
Zee Taw
Gwayt
Ywar Thar
Htu
Let Pa Nwe
Hpa Lan Taw
Pin Tone Gyi
Ywar Thit
Pay Taw (North)
Tha Yet Oke
Zee Kaing
Ah Shey Lay Ein
Yone Seik Taung
Mone Myint
Kyauk Kone
Kyun Pin Sin
Inn Daung
Thea Kone
Tha Min Chan
Than Ban Tin
Let Khoke
Gone Thaung
Kyauk Pa Taung
Be Seik
Tha Hpan Tan
Sin Su
Bu Thei
Myauk Shar Taw
Nyaung Hla
Thit Taw
Taung Inn
Ma Yoe Kone
Taung Shar Taw


AIRBM Project
National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
SOBA 3: Geomorphic zones and sampling locations, April – May 2017
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
Sentinel 2 (5/2/17)
Data Source :
Creation Date:18 Dec 2017
Towns and cities: MIMU
Sattelite: Sentinel 2
Paper Size: A4
WWF
N
L
M
N
Kilometers
0 1 2 4 6
Kulzet Chaung
Kyun Chaung
War Taw Chaung
Minhla
08:40
08:23
08:10
08:35
08:30
10:38
10:38
10:40
10:30
13:05
13:15
13:15
13:15
550
545
540
535
530
525
520
515
510
505
500
490
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36
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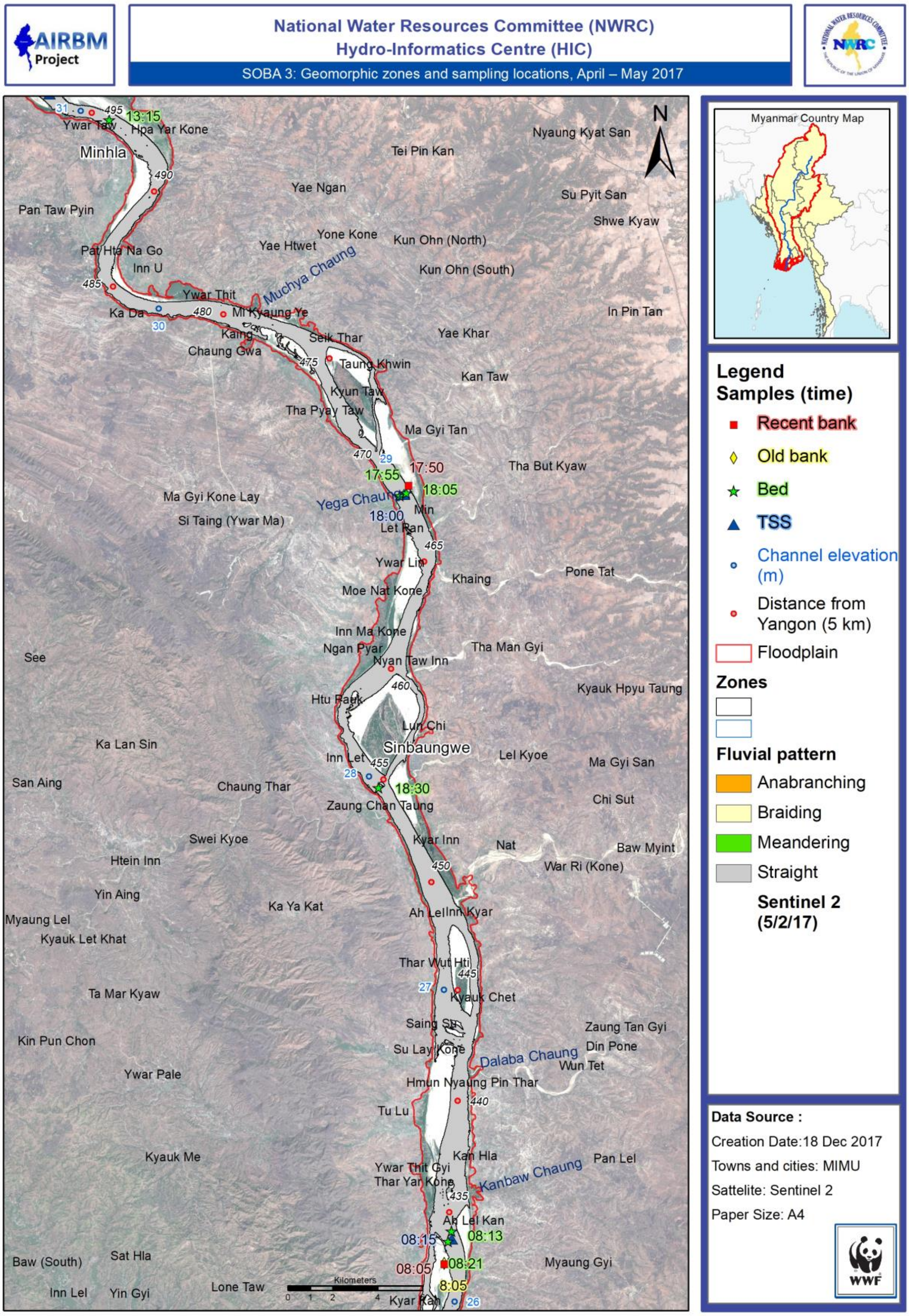
33
32
31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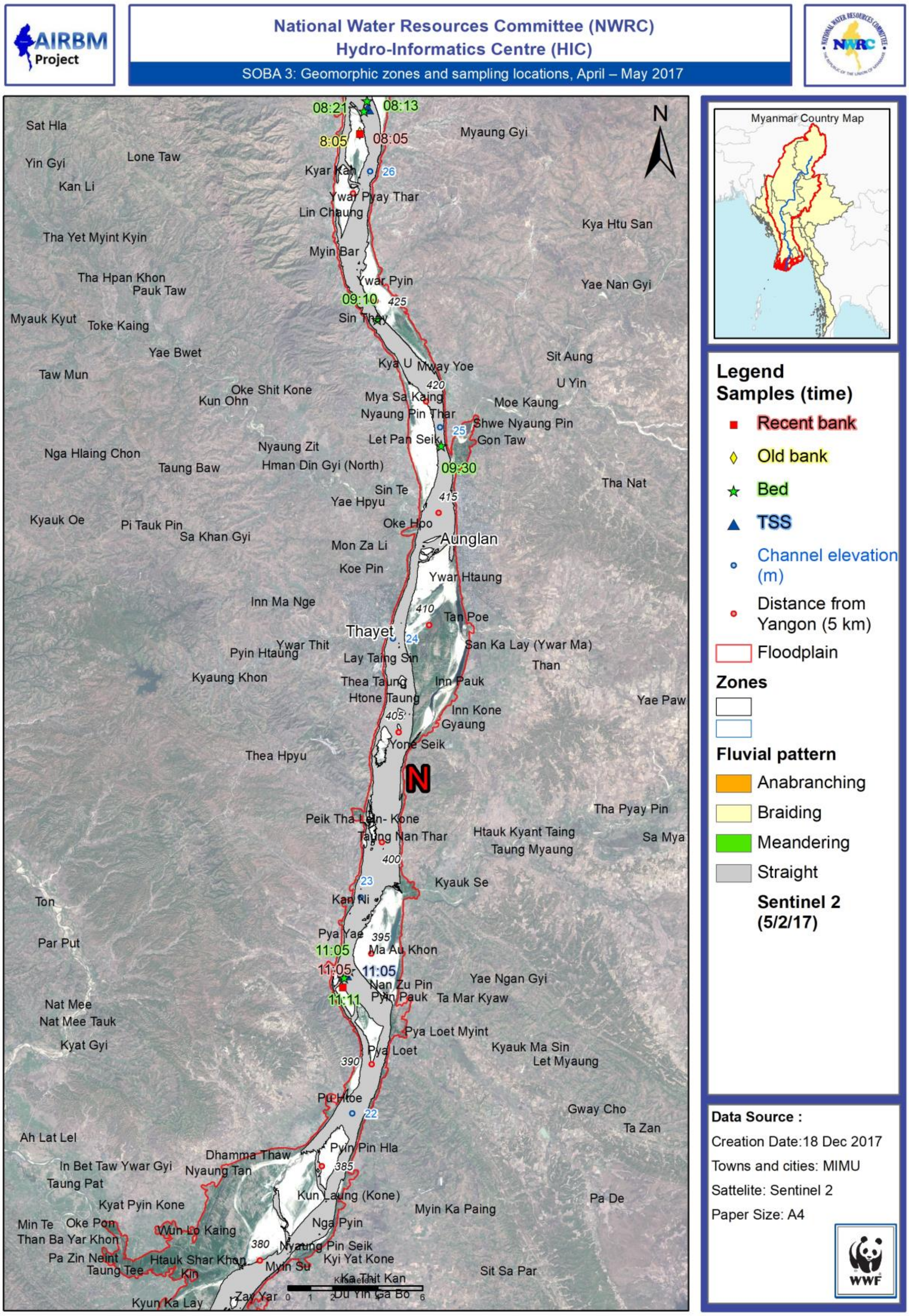
WWF
Kilometers
0 1 2 4
Minhla
Ywar Taw
Hpa Yar Kone
13:15
Tei Pin Kan
Nyaung Kyat San
Yae Ngan
Su Pyit San
Pan Taw Pyin
Shwe Kyaw
Yone Kone
Yae Htwet
Kun Ohn (North)
Kun Ohn (South)
Pat Hta Na Go
Inn U
Muchya Chaung
Ywar Thit
Ka Da
Mi Kyaung Ye
In Pin Tan
Kaing
Seik Thar
Yae Khar
Chaung Gwa
Taung Khwin
Kan Taw
Kyun Taw
Tha Pyay Taw
Ma Gyi Tan
17:50
17:55
18:05
Tha But Kyaw
Ma Gyi Kone Lay
Yega Chaung
Si Taing (Ywar Ma)
18:00
Min
Let Pan
Ywar Lin
Khaing
Pone Tat
Moe Nat Kone
Inn Ma Kone
Ngan Pyar
Nyan Taw Inn
Tha Man Gyi
See
Kyauk Hpyu Taung
Htu Pauk
Lun Chi
Sinbaungwe
Ka Lan Sin
Lel Kyoe
Ma Gyi San
Inn Let
San Aing
Chaung Thar
18:30
Zaung Chan Taung
Chi Sut
Swei Kyoe
Kyar Inn
Nat
Baw Myint
Htein Inn
War Ri (Kone)
Yin Aing
Ka Ya Kat
Myaung Lel
Ah Lel Inn Kyar
Kyauk Let Khat
Thar Wut Hti
Ta Mar Kyaw
Kyauk Chet
Saing Shi
Zaung Tan Gyi
Kin Pun Chon
Su Lay Kone
Din Pone
Dalaba Chaung
Wun Tet
Ywar Pale
Hmun Nyaung Pin Thar
Tu Lu
Kan Hla
Kyauk Me
Pan Lel
Ywar Thit Gyi
Thar Yar Kone
Kanbaw Chaung
Ah Lel Kan
08:15
08:13
08:21
08:05
8:05
Baw (South)
Sat Hla
Myaung Gyi
Lone Taw
Inn Lel
Yin Gyi
Kyar Kan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WWF
Sat Hla
Yin Gyi
Lone Taw
Kan Li
Kyar Kan
Ywar Pyay Thar
Lin Chaung
Myaung Gyi
Tha Yet Myint Kyin
Kya Htu San
Myin Bar
Tha Hpan Khon
Pauk Taw
Ywar Pyin
Yae Nan Gyi
Myauk Kyut
Toke Kaing
Sin Thay
Yae Bwet
Sit Aung
Taw Mun
Kya U
Mway Yoe
U Yin
Oke Shit Kone
Kun Ohn
Mya Sa Kaing
Moe Kaung
Nyaung Pin Thar
Shwe Nyaung Pin
Nyaung Zit
Let Pan Seik
Gon Taw
Nga Hlaing Chon
Hman Din Gyi (North)
Taung Baw
Tha Nat
Sin Te
Yae Hpyu
Kyauk Oe
Pi Tauk Pin
Oke Hpo
Sa Khan Gyi
Aunglan
Mon Za Li
Koe Pin
Ywar Htaung
Inn Ma Nge
Tan Poe
Thayet
Ywar Thit
Pyin Htaung
Lay Taing Sin
San Ka Lay (Ywar Ma)
Than
Kyaung Khon
Thea Taung
Inn Pauk
Htone Taung
Yae Paw
Inn Kone
Gyaung
Yone Seik
Thea Hpyu
Tha Pyay Pin
Peik Tha Lin- Kone
Taung Nan Thar
Htauk Kyant Taing
Taung Myaung
Sa Mya
Kyauk Se
Ton
Kan Ni
Pya Yae
Par Put
Ma Au Khon
Yae Ngan Gyi
Nan Zu Pin
Pyin Pauk
Ta Mar Kyaw
Nat Mee
Nat Mee Tauk
Pya Loet Myint
Kyat Gyi
Kyauk Ma Sin
Pya Loet
Let Myaung
Pu Htoe
Gway Cho
Ta Zan
Ah Lat Lel
Dhamma Thaw
Pyin Pin Hla
In Bet Taw Ywar Gyi
Nyaung Tan
Taung Pat
Kun Laung (Kone)
Pa De
Kyat Pyin Kone
Myin Ka Paing
Min Te
Oke Pon
Wun Lo Kaing
Nga Pyin
Than Ba Yar Khon
Nyaung Pin Seik
Kyi Yat Kone
Pa Zin Neint
Htauk Shar Khon
Myin Su
Taung Tee
Kin
Ka Thit Kan
Sit Sa Par
Zay Yar
Du Yin Ga Bo
Kyun Ka Lay
08:21
08:13
8:05
08:05
09:10
09:30
11:05
11:05
11:05
11:11
26
425
420
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415
410
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23
395
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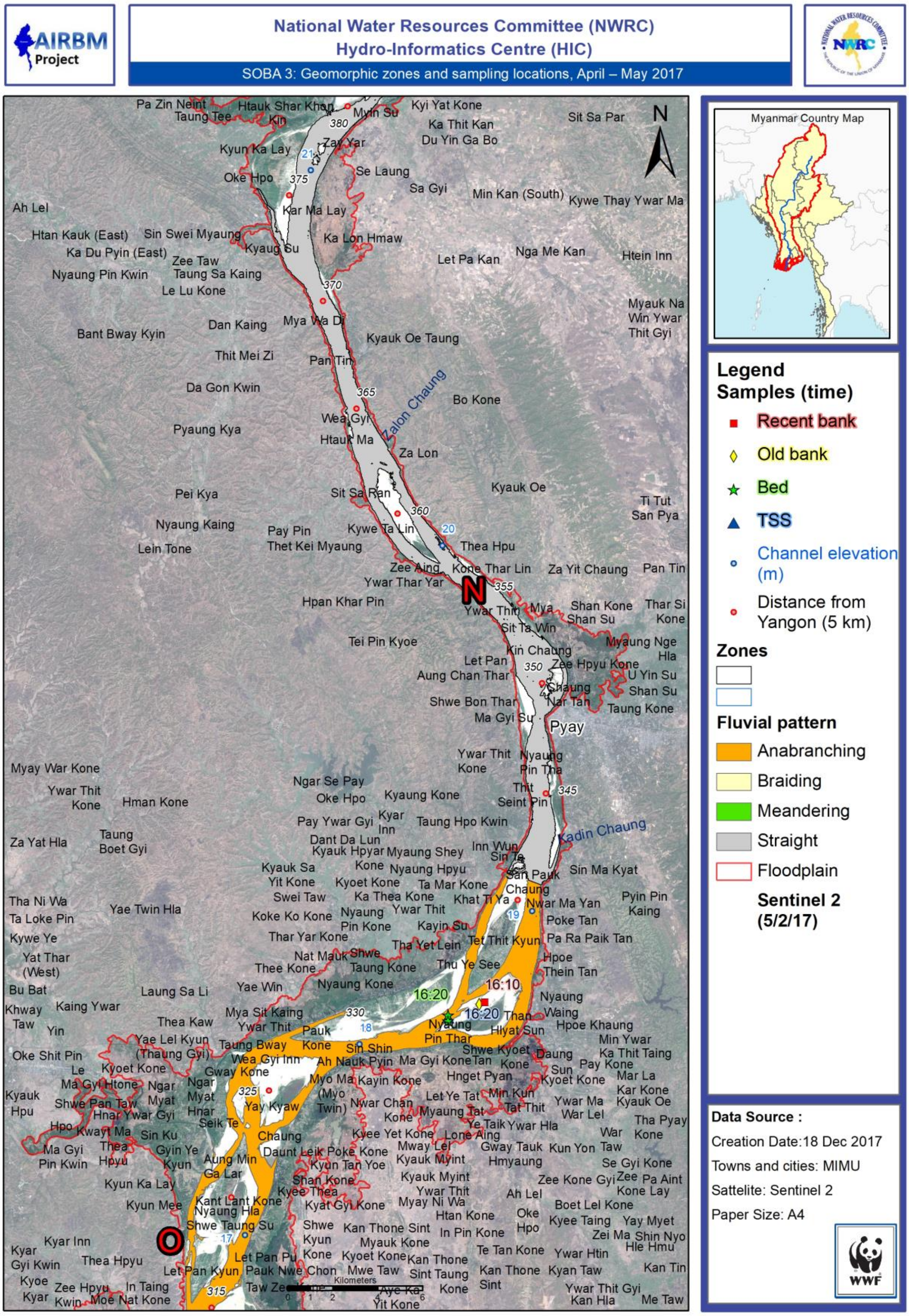
22
385
380
0 1 2 4 6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Straight
Floodplain
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Paper Size: A4
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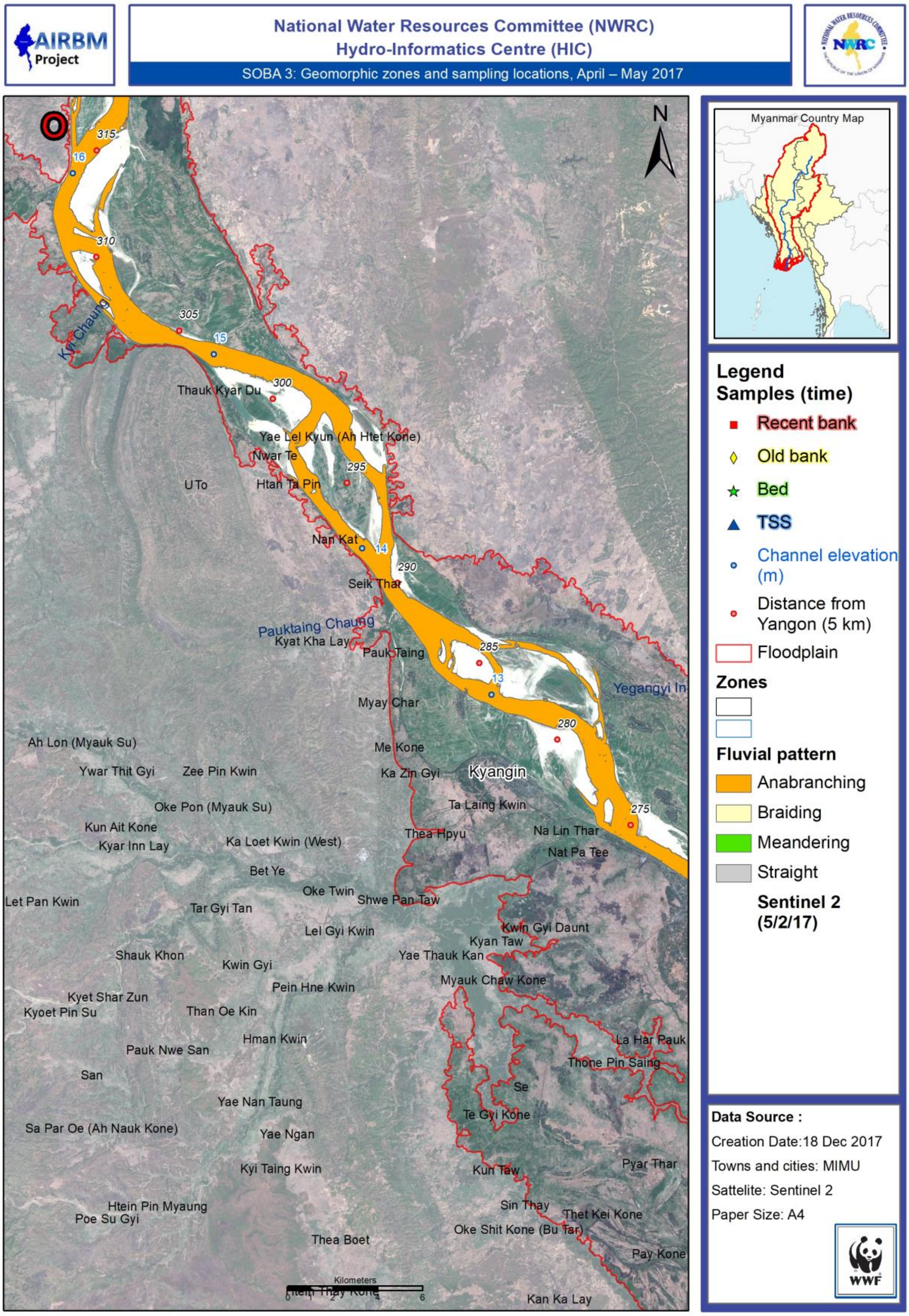
Pyay
Zalon Chaung
Kadin Chaung
Kilometers


AIRBM Project
National Water Resources Committee (NWRC)
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SOBA 3: Geomorphic zones and sampling locations, April – May 2017
O
N
315
16
310
305
15
Kyi Chaung
Thauk Kyar Du
300
Yae Lel Kyun (Ah Htet Kone)
Nwar Te
295
U To
Htan Ta Pin
Nan Kat
14
290
Seik Thar
Pauktaing Chaung
Kyat Kha Lay
Pauk Taing
285
13
Yegangyi In
Myay Char
280
Ah Lon (Myauk Su)
Me Kone
Ywar Thit Gyi
Zee Pin Kwin
Ka Zin Gyi
Kyangin
Oke Pon (Myauk Su)
Ta Laing Kwin
275
Kun Ait Kone
Kyar Inn Lay
Ka Loet Kwin (West)
Thea Hpyu
Na Lin Thar
Nat Pa Tee
Bet Ye
Let Pan Kwin
Tar Gyi Tan
Oke Twin
Shwe Pan Taw
Lel Gyi Kwin
Kwin Gyi Daunt
Kyan Taw
Shauk Khon
Kwin Gyi
Yae Thauk Kan
Myauk Chaw Kone
Pein Hne Kwin
Kyet Shar Zun
Kyoet Pin Su
Than Oe Kin
Hman Kwin
La Har Pauk
Pauk Nwe San
Thone Pin Saing
San
Se
Yae Nan Taung
Te Gyi Kone
Sa Par Oe (Ah Nauk Kone)
Yae Ngan
Kyi Taing Kwin
Kun Taw
Pyar Thar
Htein Pin Myaung
Poe Su Gyi
Sin Thay
Thet Kei Kone
Thea Boet
Oke Shit Kone (Bu Tar)
Pay Kone
Kilometers
0 2 4 6
Kan Ka Lay
Myanmar Country Map
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Old bank
Bed
TSS
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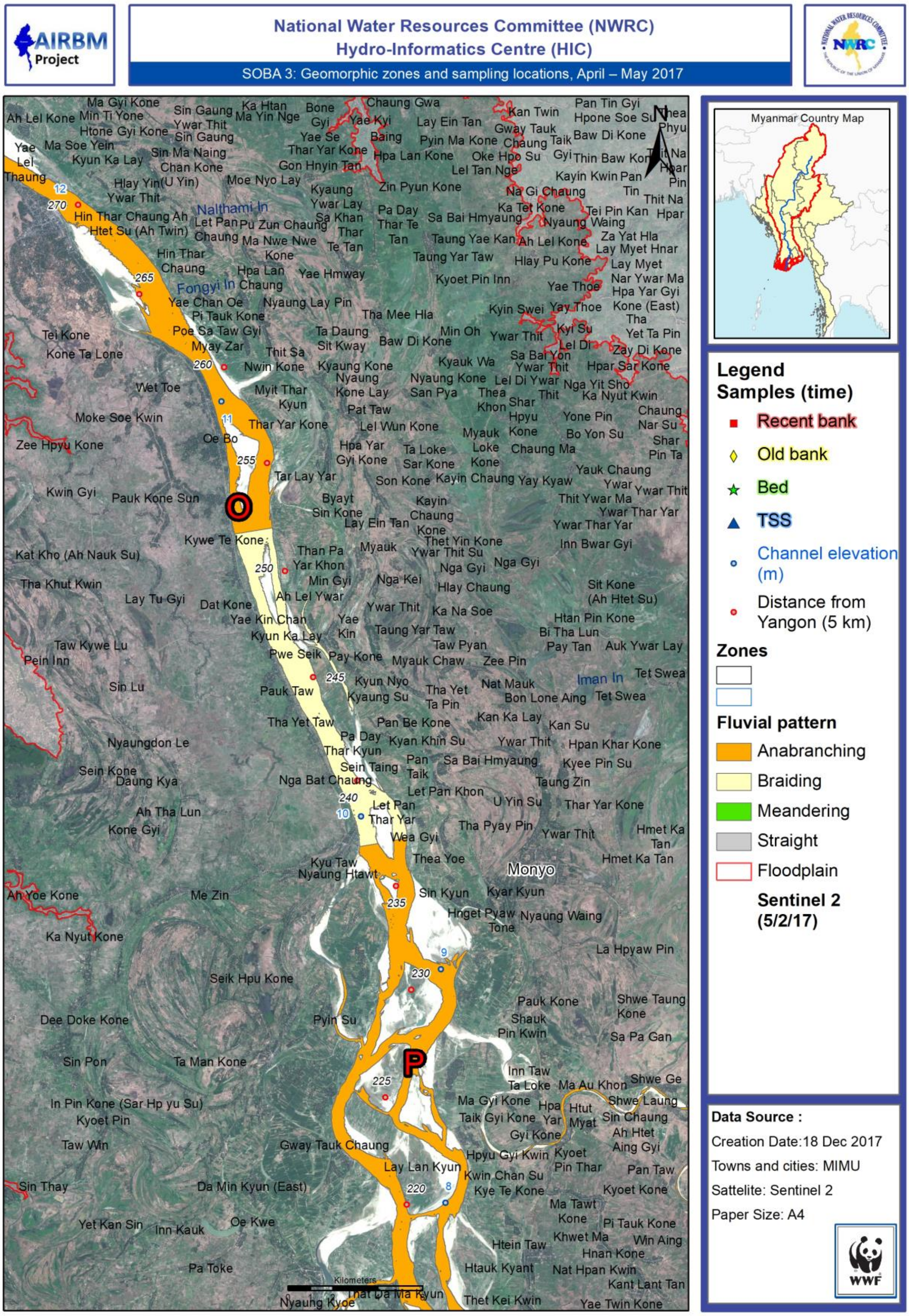
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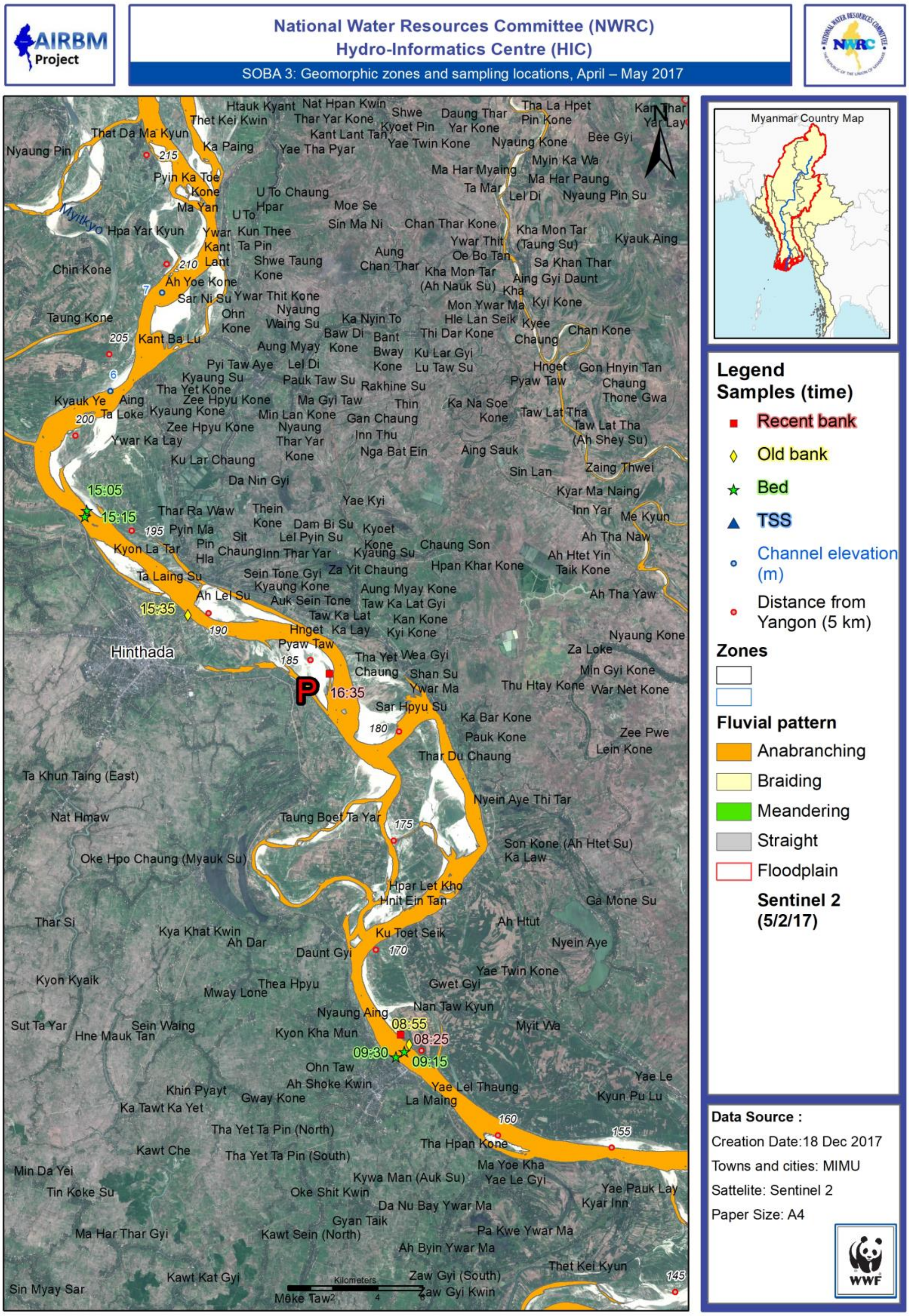
Paper Size: A4
WWF
O
P
Monyo
Kilometers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Legend
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Old bank
Bed
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Floodplain
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Paper Size: A4
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Hinthada
Myitkyo
15:05
15:15
15:35
16:35
08:55
08:25
09:30
09:15
215
210
205
200
195
190
185
180
175
170
160
155
145
Kilometers
Nyaung Pin
That Da Ma Kyun
Thet Kei Kwin
Ka Paing
Pyin Ka Toe Kone
Ma Yan
Hpa Yar Kyun
Chin Kone
Taung Kone
Kant Ba Lu
Kyauk Ye
Ta Khun Taing (East)
Nat Hmaw
Oke Hpo Chaung (Myauk Su)
Thar Si
Kya Khat Kwin
Kyon Kyaik
Sut Ta Yar
Hne Mauk Tan
Sein Waing
Khin Pyayt
Ka Tawt Ka Yet
Kawt Che
Min Da Yei
Tin Koke Su
Ma Har Thar Gyi
Sin Myay Sar
Kawt Kat Gyi
Moke Taw
Taung Boet Ta Yar
Hpar Let Kho
Hnit Ein Tan
Ku Toet Seik
Daunt Gyi
Nyaung Aing
Kyon Kha Mun
Ohn Taw
Ah Shoke Kwin
La Maing
Yae Lel Thaung
Tha Hpan Kone
Ma Yoe Kha
Yae Le Gyi
Kwya Man (Auk Su)
Oke Shit Kwin
Da Nu Bay Ywar Ma
Gyan Taik
Kawt Sein (North)
Pa Kwe Ywar Ma
Ah Byin Ywar Ma
Thet Kei Kyun
Zaw Gyi (South)
Zaw Gyi Kwin
Yae Pauk Lay
Kyar Inn
Kyun Pu Lu
Yae Le
Myit Wa
Nan Taw Kyun
Gwet Gyi
Yae Twin Kone
Nyein Aye
Ga Mone Su
Ah Htut
Son Kone (Ah Htet Su)
Ka Law
Nyein Aye Thi Tar
Thar Du Chaung
Pauk Kone
Ka Bar Kone
Sar Hpyu Su
Zee Pwe
Lein Kone
Thu Htay Kone
War Net Kone
Min Gyi Kone
Za Loke
Nyaung Kone
Ah Tha Yaw
Ah Htet Yin
Taik Kone
Ah Tha Naw
Inn Yar
Me Kyun
Kyar Ma Naing
Zaing Thwei
Sin Lan
Aing Sauk
Nga Bat Ein
Tha Yet Chaung
Wea Gyi
Shan Su
Ywar Ma
Hnget Pyaw Taw
Ka Lay
Kyi Kone
Kan Kone
Taw Ka Lat Gyi
Aung Myay Kone
Hpan Khar Kone
Chaung Son
Yae Kyi
Da Nin Gyi
Ku Lar Chaung
Ywar Ka Lay
Ta Loke
Thar Ra Waw
Pyin Ma
Kyon La Tar
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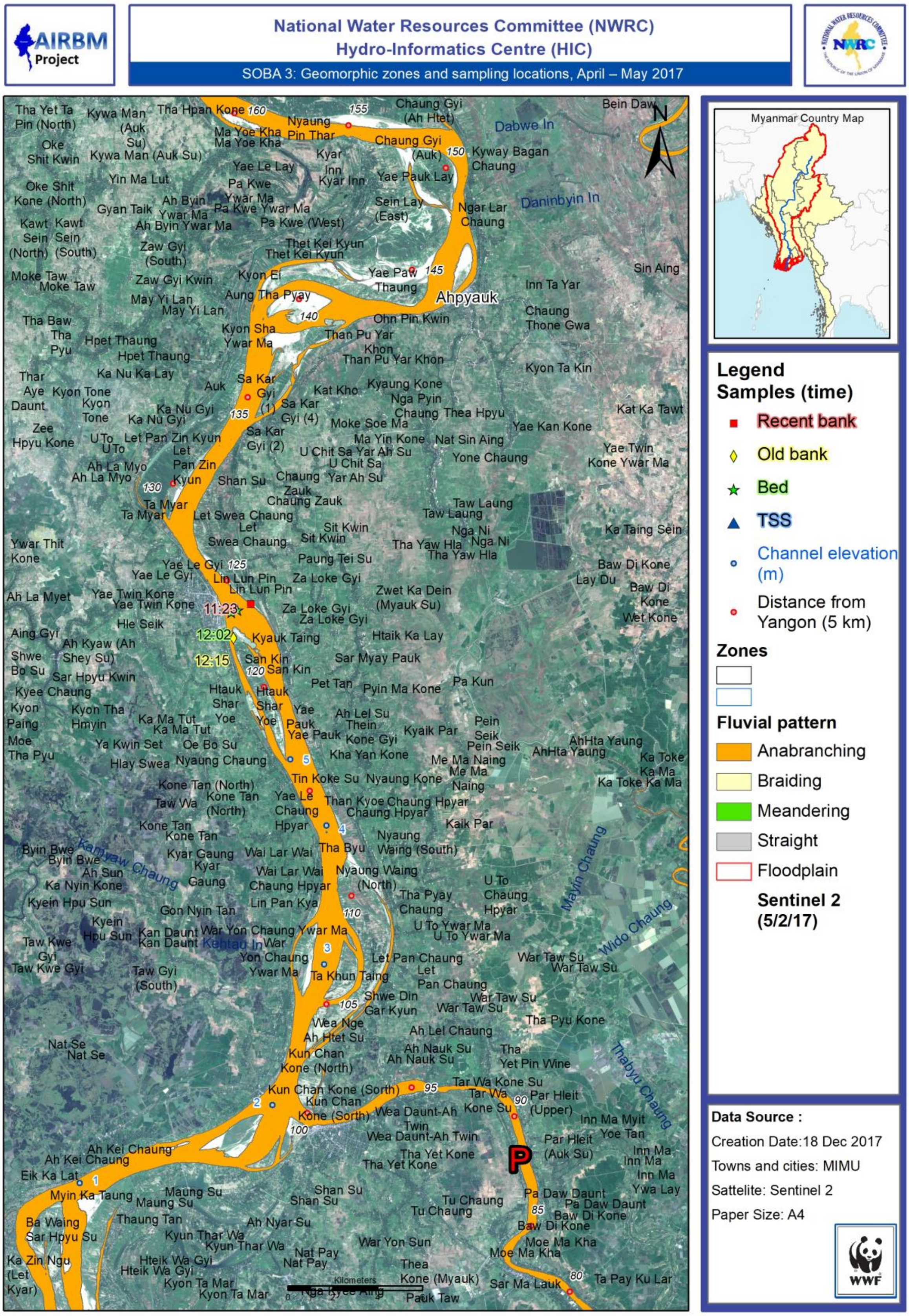
Ah Lel Su
Tha Yet Ta Pin (North)
Tha Yet Ta Pin (South)
Gway Kone
Mway Lone
Thea Hpyu
Ah Dar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SOBA 3: Geomorphic zones and sampling locations, April – May 2017
Myanmar Country Map
Legend
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Zones
Fluvial pattern
Anabranching
Braiding
Meandering
Straight
Floodplain
Sentinel 2 (5/2/17)
Data Source :
Creation Date:18 Dec 2017
Towns and cities: MIMU
Sattelite: Sentinel 2
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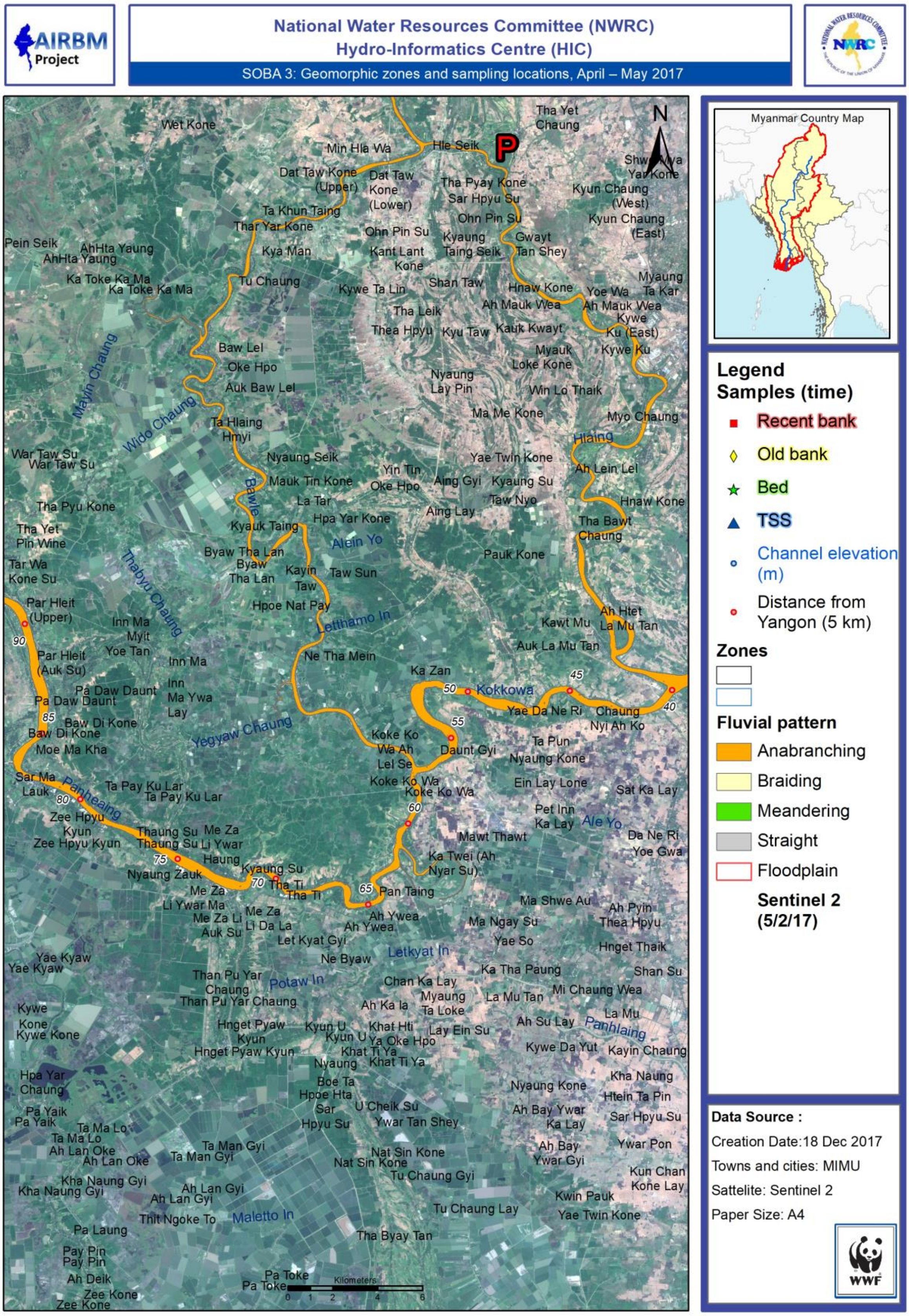
Kilometers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90
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Wet Kone
Tha Yet Chaung
Min Hla Wa
Hle Seik
Dat Taw Kone (Upper)
Dat Taw Kone (Lower)
Tha Pyay Kone
Sar Hpyu Su
Ta Khun Taing
Thar Yar Kone
Ohn Pin Su
Kya Man
Kant Lant Kone
Kyaung Taing Seik
Gwayt Tan Shey
Kyun Chaung (West)
Kyun Chaung (East)
Pein Seik
AhHta Yaung
Ka Toke Ka Ma
Tu Chaung
Kywe Ta Lin
Shan Taw
Hnaw Kone
Yoe Wa
Myaung Ta Kar
Ah Mauk Wea
Tha Leik
Thea Hpyu
Kyu Taw
Kauk Kwayt
Kywe Ku (East)
Kywe Ku
Baw Lel
Oke Hpo
Auk Baw Lel
Myauk Loke Kone
Nyaung Lay Pin
Win Lo Thaik
Mayin Chaung
Wido Chaung
Ta Hlaing Hmyi
Ma Me Kone
Myo Chaung
Hlaing
War Taw Su
Nyaung Seik
Yae Twin Kone
Ah Lein Lel
Mauk Tin Kone
Yin Tin Oke Hpo
Aing Gyi
Kyaung Su
Taw Nyo
Bawle
La Tar
Aing Lay
Hnaw Kone
Tha Pyu Kone
Hpa Yar Kone
Kyauk Taing
Tha Bawt Chaung
Tha Yet Pin Wine
Alein Yo
Byaw Tha Lan
Pauk Kone
Tar Wa Kone Su
Thabyu Chaung
Kayin Taw
Taw Sun
Par Hleit (Upper)
Hpoe Nat Pay
Inn Ma Myit
Letthamo In
Kawt Mu
Ah Htet La Mu Tan
Par Hleit (Auk Su)
Yoe Tan
Inn Ma
Ne Tha Mein
Auk La Mu Tan
Pa Daw Daunt
Inn Ma Ywa Lay
Ka Zan
Kokkowa
Yae Da Ne Ri
Chaung
Nyi Ah Ko
Baw Di Kone
Yegyaw Chaung
Koke Ko Wa Ah Lel Se
Daunt Gyi
Ta Pun
Nyaung Kone
Moe Ma Kha
Sar Ma Lauk
Panhlaing
Ta Pay Ku Lar
Koke Ko Wa
Ein Lay Lone
Sat Ka Lay
Zee Hpyu Kyun
Pet Inn Ka Lay
Ale Yo
Thaung Su
Me Za Li Ywar Haung
Mawt Thawt
Da Ne Ri Yoe Gwa
Ka Twei (Ah Nyar Su)
Nyaung Zauk
Kyaung Su
Tha Ti
Pan Taing
Ma Shwe Au
Me Za Li Ywar Ma
Me Za Li Auk Su
Me Za Li Da La
Ah Ywea
Ma Ngay Su
Ah Pyin Thea Hpyu
Let Kyat Gyi
Yae So
Yae Kyaw
Ne Byaw
Letkyat In
Hnget Thaik
Than Pu Yar Chaung
Potaw In
Chan Ka Lay
Ka Tha Paung
Shan Su
Myaung Ta Loke
La Mu Tan
Mi Chaung Wea
Kywe Kone
Ah Ka la
Ah Su Lay
La Mu
Hnget Pyaw Kyun
Kyun U
Khat Hti Ya Oke Hpo
Lay Ein Su
Kywe Da Yut
Kayin Chaung
Khat Ti Ya
Nyaung Khat Ti Ya
Hpa Yar Chaung
Boe Ta Hpoe Hta Sar
Nyaung Kone
Kha Naung
Htein Ta Pin
U Cheik Su
Hpyu Su
Ywar Tan Shey
Ah Bay Ywar Ka Lay
Sar Hpyu Su
Pa Yaik
Ta Ma Lo
Ah Lan Oke
Ta Man Gyi
Nat Sin Kone
Ah Bay Ywar Gyi
Ywar Pon
Kun Chan Kone Lay
Tu Chaung Gyi
Kha Naung Gyi
Ah Lan Gyi
Kwin Pauk
Yae Twin Kone
Tu Chaung Lay
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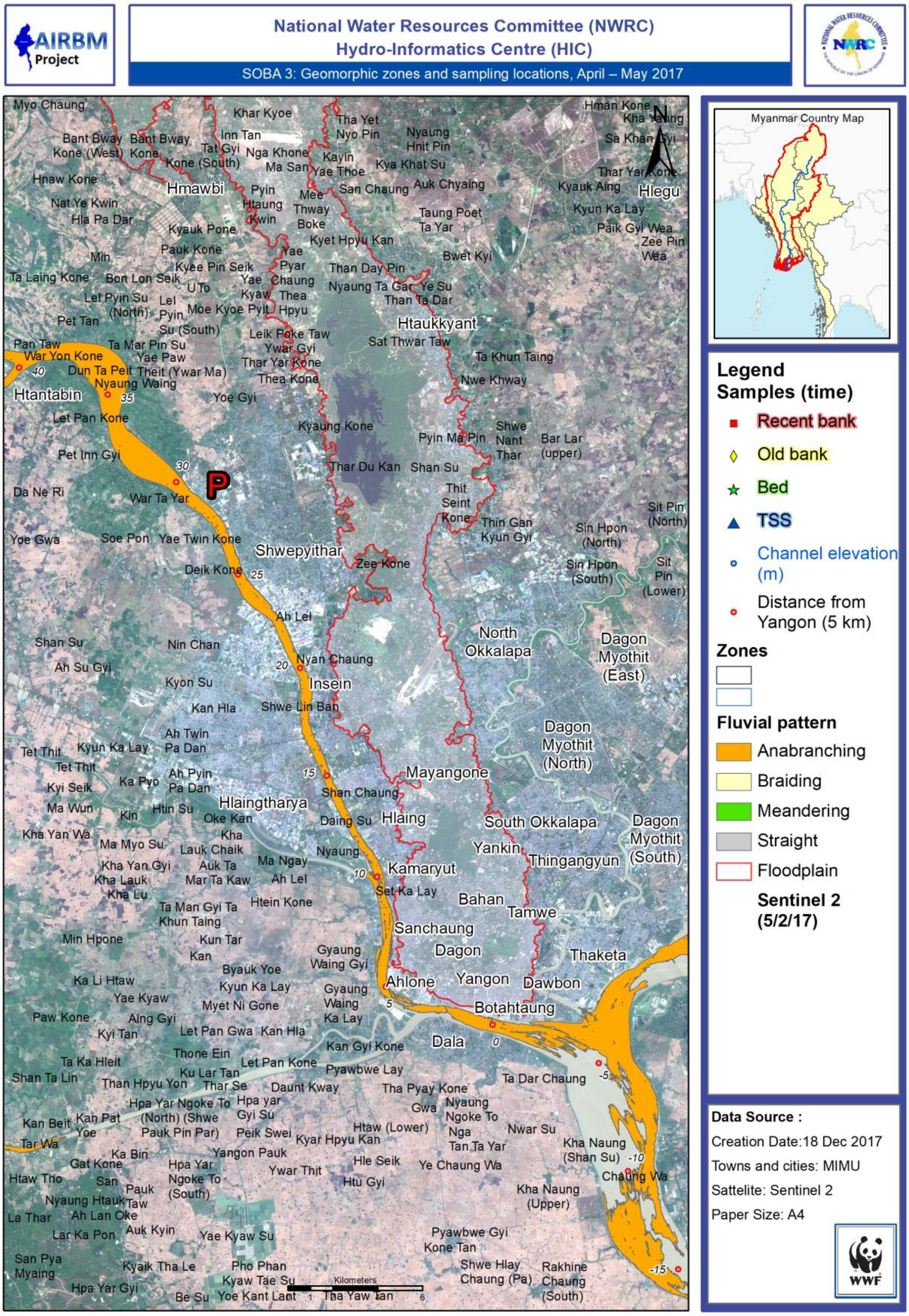
Maletto In
Pa Laung
Tha Byay Tan
Pay Pin
Ah Deik
Pa Toke
Zee Kone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Kilometers
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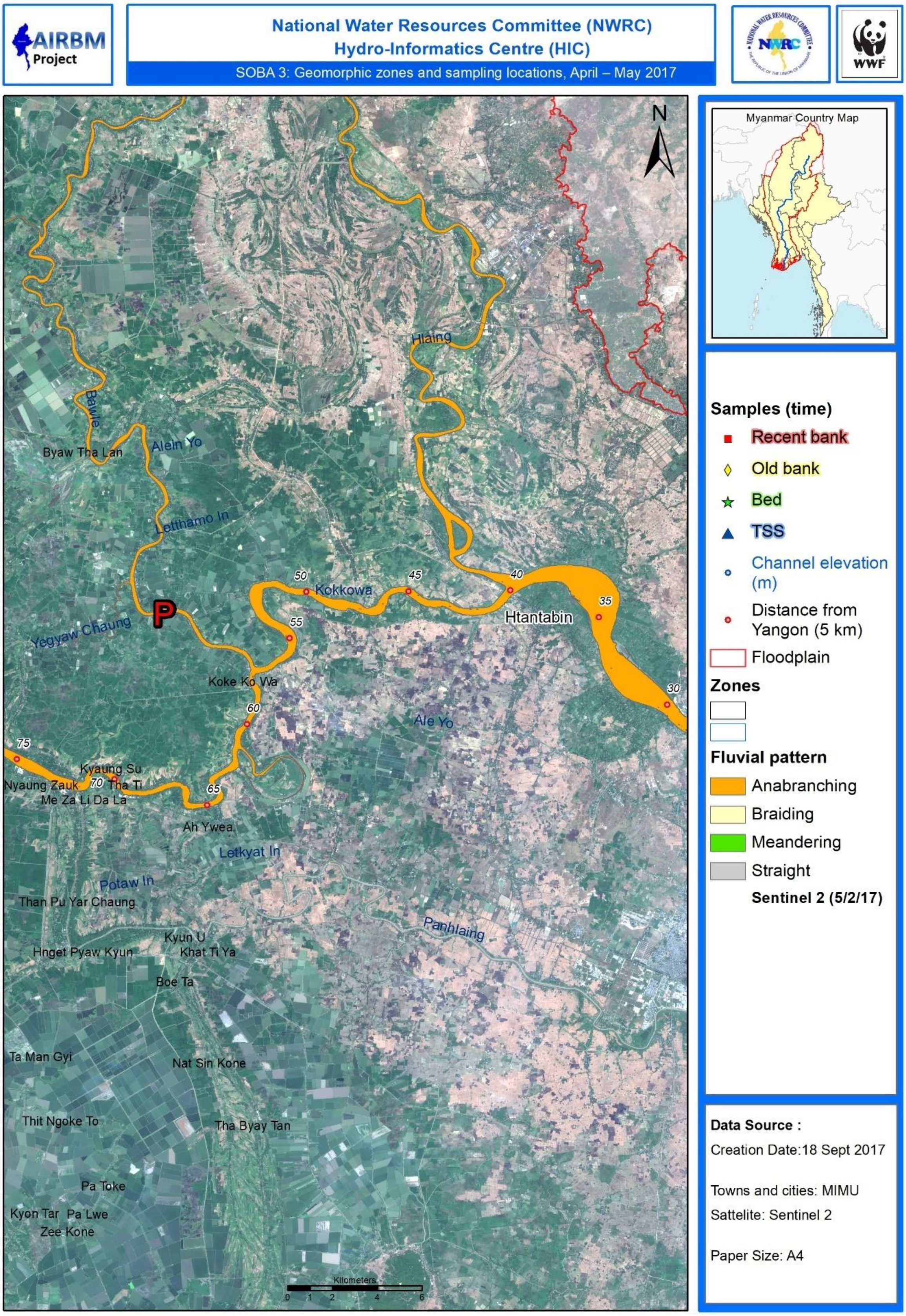
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Myanmar Country Map
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Bawle
Byaw Tha Lan
Alein Yo
Letthamo In
Yegyaw Chaung
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Kokkowa
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Koke Ko Wa
Ale Yo
Kyaung Su
Nyaung Zauk
Tha Ti
Me Za Li Da La
Ah Ywea
Letkyat In
Potaw In
Than Pu Yar Chaung
Panhlaing
Hnget Pyaw Kyun
Kyun U
Khat Ti Ya
Boe Ta
Ta Man Gyi
Nat Sin Kone
Thit Ngoke To
Tha Byay Tan
Pa Toke
Kyon Tar
Pa Lwe
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Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
Zones
Fluvial pattern
Anabranching
Braiding
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Sentinel 2 (5/2/17)
Data Source :
Creation Date:18 Sept 2017
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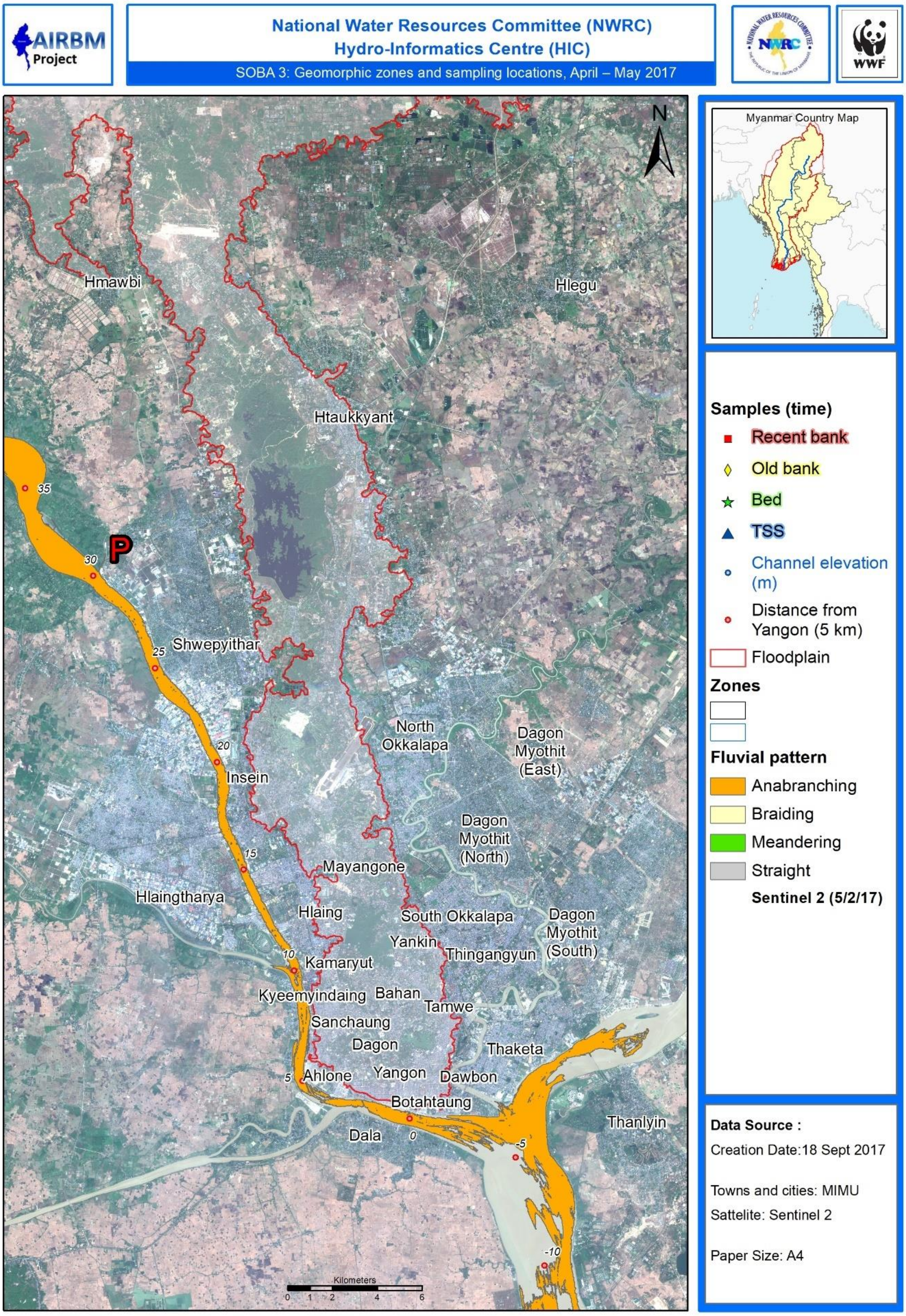
Paper Size: A4


AIRBM Project
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SOBA 3: Geomorphic zones and sampling locations, April – May 2017
WWF
Myanmar Country Map
N
Hmawbi
Hlegu
Htaukkyant
35
30
P
25
Shwepyithar
20
Insein
North Okkalapa
Dagon Myothit (East)
Dagon Myothit (North)
15
Mayangone
Hlaingtharya
Hlaing
South Okkalapa
Dagon Myothit (South)
Yankin
Thingangyun
10
Kamaryut
Kyeemyindaing
Bahan
Tamwe
Sanchaung
Dagon
Thaketa
5
Ahlone
Yangon
Dawbon
Botahtaung
Dala
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-5
Thanlyin
-10
Kilometers
0 1 2 4 6
Samples (time)
Recent bank
Old bank
Bed
TSS
Channel elevation (m)
Distance from Yangon (5 km)
Floodplain
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Paper Size: A4

ANNEX 3 – SATELLITE IMAGERY ANALYSIS METHODS

METHDOLOGY FOR DETERMINING CHANNEL WIDTH

METHDOLOGY FOR DETERMINING LOCATIONS OF SAND AND GRAVEL MINING

METHODOLOGY – SATELLITE INVESTIGATION TO DETERMINE RIVER CHANNEL WIDTH DURING THE DRY SEASON

The channel width was measured through the analysis of satellite images during the low-flow period, i.e. between 30 January and 11 March. A total of 17 years of images were used, corresponding to the Tropical Rainfall Measuring Mission data series (Table 13). This period was selected due to the high-quality and cloud-free nature of the available imagery. These images yielded high-quality results that are internally consistent. Width measurements were not carried out between the delta head and the sea because of the large number of distributaries; therefore, the analysis started about 300 km upstream of the delta front.

Using the Centerline tool from ArcGIS developed by Roux et al., (2013), the axis, or centerline, of the trunk channel was established along the entire length of the Ayeyarwady River for the 17 satellite image mosaics corresponding to the 17 years (Table 13). Midstream islands were included in the measurements in order to obtain only one centerline encompassing all the channels for every year. The Width tool of the Metrics assessments module (Roux et al., 2013) was then used to measure channel width for single and multiple threads, along a line perpendicular to the centerline. One width measurement was obtained every 100 m along the river to improve precision and reduce bias in areas where portions of the sinuous channels lie perpendicular to the centerline, and thus generate artefacts affecting the real width of the channel. Finally, the measured 100 m width data were averaged over channel distances of 1 km to limit the artefacts described above and to scale with the length of the Ayeyarwady River.

Table 13 - Satellite images available for measuring the Ayeyarwady River width

Year	Landsat	Eastern satellite track	Western satellite track
2016	L8	4 Feb	11 Feb
2015	L8	17 Feb	24 Feb
2014	L8	2 Mar	21 Feb
2011	L4-5 TM	28 Jan	21 Jan
2010	L4-5 TM	3 Feb	10 Feb
2009	L4-5 TM	16 Feb	7 Feb
2008	L4-5 TM	1 Mar	8 Mar
2005	L4-5 TM	5 Feb	12 Feb
2004	L4-5 TM	19 Feb	26 Feb
2003	L7 SLC-on	24 Feb	15 Feb
2002	L7 SLC-on	5 Feb	12 Feb
1998	L4-5 TM	2 Feb	25 Feb
1997	L4-5 TM	30 Jan	22 Feb
1996	L4-5 TM	29 Feb	7 Mar
1994	L4-5 TM	11 Mar	2 Mar
1990	L4-5 TM	16 Mar	23 Mar
1988	L4-5 TM	7 Feb	14 Feb

Table 14 - Satellite images available for measuring the Chindwin River width

Year	Landsat	Eastern satellite track	Western satellite track
2016	L8 OLI	4 Feb	11 Feb
2015	L8 OLI	17 Feb	24 Feb
2014	L8 OLI	2 Mar	21 Feb
2011	L4-5 TM	28 Jan	21 Jan
2010	L4-5 TM	3 Feb	10 Feb
2009	L4-5 TM	16 Feb	7 Feb
2008	L4-5 TM	1 Mar	8 Mar

Year	Landsat	Eastern satellite track	Western satellite track
2005	L4-5 TM	5 Feb	12 Feb
2004	L4-5 TM	19 Feb	26 Feb
2003	L7 SLC-on	24 Feb	15 Feb
2002	L7 SLC-on	5 Feb	12 Feb
1998	L4-5 TM	2 Feb	25 Feb
1997	L4-5 TM	30 Jan	22 Feb
1996	L4-5 TM	29 Feb	7 Mar
1994	L4-5 TM	11 Mar	2 Mar
1990	L4-5 TM	16 Mar	23 Mar
1988	L4-5 TM	7 Feb	14 Feb

For the measurement of channel width during the 30-year average water extent, the active channel, or the sandbar with the water bodies for the width, was taken into account. The sandbars were extracted with the red band using a threshold which was similar for most years, with a few exceptions (see Table 18).

Given the impossibility of obtaining cloud-free satellite images during the flood season, and the braided nature of many channel reaches in low-flow conditions, channel bars were combined with open water bodies to estimate average channel width. The sandbars exposed during the dry season correspond to areas where high-stage flow is sufficiently powerful to move the sediment and prevent plant colonisation. All measures were taken from the same point (red dots in Figure 62) in order to facilitate comparison between years.

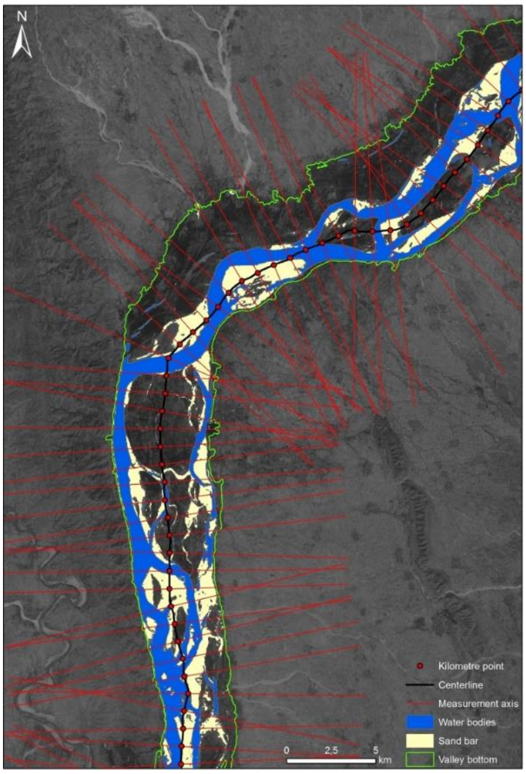

Figure 1 - Method for the measurement of channel width

METHODOLOGY – SATELLITE INTERPRETATION OF SAND MINING ACTIVITIES IN THE AYEYARWADY

Between Mandalay and Danubyu, the SOBA 3 field team observed numerous dredges grouped together with many barges at varying distances from the dredges. This configuration of dredges and neighbouring barges have a shape which is unique to sand and gravel mining in the river, and has been exploited to provide a high-level investigation into the distribution and intensity of sand mining in the middle and lower Ayeyarwady.

Satellite images provide a snapshot of sand extraction and identify the major areas of gravel or sand extraction, within the limitations of the imagery. The Sentinel 2 satellite imagery has a resolution of 10 m, which is sufficient to allow relatively accurate identification of the boats involved in sand extraction. This satellite is only two years old, so images are only available from 23 November 2015 for the Ayeyarwady. Other available imagery was evaluated but considered inappropriate for the temporal and spatial scales required.

The Sentinel 2 imagery allows delineation of large boats, such as barges, which are distinct from other boats, but the images cannot provide information on the type(s) of material transported. Dredges can be detected and identified even if they are very small, due to the specific position and relationship to other boats (**Error! Reference source not found.**). Dredges cannot be accurately identified if they occur singularly and are removed from clusters of other dredges.

Figure 0.1 - Satellite images showing distribution and relationship between barges and dredges
Barges are grouped together and shown in the red circles. The larger barges are located nearby and circled in black.

Due to the limited number of satellite images available and the presence of clouds in some images, only seven different dates were identified as appropriate for analysis. To analyse the images, the near-infrared and short wave infrared spectral bands were interpreted using the Normalised Difference Water Index method. This method was chosen because it is a recognised approach for detecting non-water objects. Only boats in the river channel were were identified as those near the riverbank may or may not have been actively involved in sand extraction. The area included in the analysis was between the Inwa bridge near Mandalay and the Bo Myat Tun Bridge near Nyaungdon, close to the head of the delta. This area was targeted because most of the the sand/gravel mining activity observed during the field survey was downstream of Mandalay.

The results from the satellite analysis were used to refine the locations for implementation of the sand mining survey.

ANNEX 4 – SAND MINING SURVEY AND FIELD REPORT

Aggregate Mining Survey

DISTRIBUTION SITE QUESTIONS

1. General distribution site information
   State or region:
   Township:
   Nearest town or village:
   Company name (if applicable):
   Name of person interviewed (not required):

   Provide GPS point and photos.

2. What is extracted? Stored? Transported?

Category of sediment			Present price per Sud (Gyin)?
Fine sand	Yes □	No □	
Construction sand	Yes □	No □	
Gravel	Yes □	No □	
Pebbles	Yes □	No □	

3. If transported, what is the means of transport? By barge, large truck, small truck, or rail?

4. Where is the material from?

Material	River	Location/state/township
Fine sand		
Construction sand		
Gravel		
Pebble		

5. Approximate size of storage or extraction site:

6. What is the number of people working on site?

Number of full time staff	In mining	7.2.1 In a distribution centre
Fewer than 3 people		
Four to 10 people		
More than 11 people		

7. What equipment vehicles were operating on site? Take photos if possible.

Type of equipment	Extraction method (if known) and number	Distribution sites and number	Comments
Small tractor/light truck			
Large truck			
Mechanical shovel/wheel loader			
Conveyor belt			

Dredger			
Bargest			

8. Number of years of distribution operation:

This is the first year □
More than 1 but less than 5 □
More than 5 but less than 10 □
More than 10 □
Do not know □

9. Has the distributor always received material from the same locations?

10. How is material transported from extraction site to distribution site?

If by barge, what is size of barge? Take photo if possible.

11. Calendar of operations:

a. When can you obtain each category of material? (G = Gravel, S = Sand)
b. When is demand greatest and lowest?

Type	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
No operation												
Limited operation												
Intensive operation												

12. Is there a difference in price between months or seasons?

13. What is the most sought-after grain-size?

14 Is there ever a problem obtaining supply?

15. Estimation of quantities distributed annually from site. Quantity can be in tons, cubic metres or truckloads (if truckload, take photo of the standard vehicle).

7.2.2 Material	Approximate quantity sold/year
Fine sand	
Construction sand	
Gravel	
Pebbles	

16. How many other distributors are there in this area?

17. What is the **demand** trend for each produced category?

Category	Trend			
7.2.3 Fine sand	Same every year □	Increasing □	Decreasing □	Do not know □
7.2.4 Coarse sand	Same every year □	Increasing □	Decreasing □	Do not know □
7.2.5 Gravel	Same every year □	Increasing □	Decreasing □	Do not know □
Pebbles	Same every year □	Increasing □	Decreasing □	Do not know □

18. What is the **availability** trend for each material?

Category	Trend in Availability	Trend in Availability	Trend in Price
Fine sand			
Coarse sand			
Gravel			
Pebbles			

19. Changes to supply: Do you receive material from more than one extraction site?

    Has this changed over time?
    Increase in supply sites because of growing demand? □
    Decrease supply sites because of replenishment rates? □
    Change in supply sites but no increase or decrease □

20. Have you observed an increase in different sizes in the gravels or pebbles supplied?

EXTRACTION SITE QUESTIONS

1. Nature of the extraction/general information about the site
   State or region:
   Township:
   Nearest town or village:
   Company name (if applicable):
   Name of person interviewed (not required):

   Provide GPS point and photos.

2. What size material is targeted for extraction?
3. Is this led by market demand or availability on site?
4. Are the different categories of materials found at different locations in the site, e.g. emerged islands, beaches, riverbanks, thresholds, rapids, different depths under water, and at different places in the riverbed?

Category	Location
Fine sand	
Coarse sand	
Gravel	
Pebbles	

5. If different categories are available on site, do you specialise in one (or two) grain-size(s) only, or will you extract whatever is available?
6. Estimation of quantities produced annually, per category:
7. Where are the best extraction sites in this area?
8. Is there competition for the concessions on the best sites?
9. How are concessions distributed?
10. To your knowledge, are there any other active in-stream dredging operations within ten kilometres of this operation?

Yes □ No □

List any other operations on a separate page.

11. How do you identify the sites that will be good for extraction, e.g. downstream areas with lateral erosion? Are they identified empirically?
12. What is the availability trend for each produced category?

Category	Trend			
7.2.6 Fine sand	Same every year □	Increasing □	Decreasing □	Do not know □
7.2.7 Coarse sand	Same every year □	Increasing □	Decreasing □	Do not know □
7.2.8 Gravel	Same every year □	Increasing □	Decreasing □	Do not know □
Pebbles	Same every year □	Increasing □	Decreasing □	Do not know □

13. Are changes to the river occurring? If so, where in the riverbed are those changes occurring, e.g. emerged islands, beaches, riverbanks, thresholds, rapids, different depths under water, or at different places in the riverbed?

14. Have the quantities extracted over time changed by:

    a. An increase in extraction/sales because of growing demand? □
    b. A decrease because of reduced replenishment rates? □
    c. Other □

If other, please describe:

15. Has there been a change in the depth for extraction (e.g. a need to dredge deeper) and/or are islands disappearing or changing shape?

Yes □ No □

If yes, please describe:
Can you estimate the increase or decrease in depth, by 50 cm, 1 m, 1.5 m, or 2m?

16. Have you observed changes to the size of gravels or pebbles being extracted?
17. Did you observe silt at extraction sites of other categories, such as fine sand, coarse sand, or gravel)?
18. Are taxes paid on quantities extracted?

Summary of Aggregate Mining (Sand and Gravel) Survey

The Sand and Gravel Mining Survey was conducted from 27 July to 19 August 2017. The questionnaire survey method used to collect information from the sand and gravel distribution centres and visited throughout this survey were chosen selected on Central Ayeyarwady River Basin (Mandalay and Sagaing), Lower Ayeyarwady Basin (Pyay and Shwe Taung), Ayeyarwady Delta (Hinthada, Zalon, Danubyu and Nyaungdone), and Yangon.

Central Ayeyarwady River Basin (Mandalay and Sagaing)

A total of 29 main distributors are engaged in construction sand mining from the Ayeyarwady River in Mandalay. Sand extraction sites are located at the main channel of Ayeyarwady River, near Mandalay and use a dragging boat (10 to 30 Gyins/~12 to 85 m^3) 3 to 10 times a day. The extraction sites map was designed by DWIR. Daily extraction for construction sand in a large operation is about 80 to 120 Gyins/~226 to 339 m^3, and for small and medium is about 20 to 60 Gyins/~56 to 169 m^3. The construction sand and coarse sand extracted from the Ayeyarwady River was used locally for construction purposes. The construction sand is distributed to Mandalay and occasionally distributed to Maymyo, Taunggyi, Lashio, and some areas in Shan State. Only four distributors are engaged in fine sand/silt extracted from the top layer of new deposited island form Ayeyarwady River around Mandalay and Mingun. Daily extraction for fine sand small and medium are about 3 to 6 Gyins/~8 to 17 m^3. The very fine sand/silt extracted from the Ayeyarwady River was used locally for gardening purposes. An estimated total number of ~3 to 7 labourers work at the one sand mining distribution centre and 6 to 10 labourers work in one boat at extraction sites in Mandalay. All distribution centres use a mechanical wheel loader and transport by light tracks. The annual maximum quantity of construction sand extraction is noticed approximates for ~1,650,654 m^3 and very fine sand/silt extraction is 19.626 m^3 of sand each is mined by Mandalay.

A total of three main distributors are engaged in construction sand mining from the Ayeyarwady River in Sagaing. Sand extraction sites are located at the downstream of Sagaing Bridge of Ayeyarwady River near Sagaing and they used (8 to 15 Gyins/~22 to 42 m^3) dragging boat by four to five times a day. The annual maximum quantity of construction sand extraction is noticed approximates for ~232,414 m^3 is mined by Sagaing.

Extraction is year-round, but operation is stopped only a few days when water level is above safe level, especially during monsoon season (June, July, August, and September). Demand is highest in open seasons, but trend over the past ten years is highest and recently from last two years start declining because of less construction and increasing distributors. The trend of sand extraction is going up and demand of sand is decreasing. An estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 3,000 to 4,000 kyats, Coarse sand is 5,000 kyats and fine sand price is 23,000 to 35,000 kyats. For licensing, registration is be done at DWIR, Mining Department and State/Division General Administration Department. Even, DWIR sometimes request that sand dredging boats owners move their dredge boats near shallow water location to extract the sand during dry season to get safe navigable water depths for vessels.

Figure 1.1 Mandalay and Sagaing Sand Mining Sites and Myitnge River Gravel site

Over the past ~10 to 15 years they used River Gravel from Migyaungye, Magway Division and after that do not used in River Gravel in Mandalay. They used Chipping Limestone for all construction purposes in Mandalay Division. There is no gravel mining in the Ayeyarwady River. Only gravel extraction small business at Myitnge River in Mandalay. Myitnge River gravel mining is not an intensive operation. There are four family businesses are found around Shwe Sar Yan Pagoda besides of Myitnge River. They usually go to the upstream near 6 to 7 miles mini beach resort area and downstream Nagaryone pagoda and Mone Taw village with small boats and collected if there is any size of demand offer from customers. Estimate of selling price shows that 1 Gyins/2.83 m3 per gravel price is ~400,000 to 800,000 kyats and pebble price is ~400,000 to 600,000 kyats. The different sizes of Gravel and Pebbles from Myitnge River extracted were used locally and sometimes transport to Shan State, Mandalay, and Yangon. Gravel demand for decoration for hotels, construction sites and water purification processes. Estimate of total number ~10 to 15 villagers are working in at the Gravel mining family business.

Lower Ayeyarwady Basin (Pyay and Shwedaung)

A total of five main distributors are engaged in construction Sand and Gravel Mining from the Ayeyarwady River in Pyay. Sand extraction sites are located at the main channel of Ayeyarwady River, upstream of Shwe Bon Thar area at Pyay and they used (7 to 20 Gyins/~19 to 56 m^3) dragging boat by 2 to 4 times a day. Gravel extraction sites are located at ~8 to 10 miles upstream of Phoe Oo Taung and Sissaryan village Kamma Town, Ayeyarwady River and they used (7 to 20 Gyins/~19 to 56 m^3) two dragging boats one time per day allows to extract from that sites. Extraction sites map designed by DWIR. Daily extraction for construction sand large operation is about (60 to 100 Gyins/~169 to 283 m^3), and Coarse sand extraction is about (8 to 15 Gyins/~22 to 42 m^3). Estimate of total number ~5 to 10 labourers are working in at the one sand distribution centres and 40 to 100 temporary workers and 8 to 12 labourers are working in one boat at extraction sites in Pyay. The construction sand and coarse sand and gravel from Ayeyarwady River extracted was used locally for construction purposes. The large size Gravel is sent to the Government project of four dams (Taung Nawain, Myauk Nawin, Taung Nyo and Wal Gyi) construction sites near Pyay Township.

Annual maximum quantity of construction sand extraction is noticed approximates for ~232,414 m^3 and Gravel extraction ~23,772 m^3 is mined by Pyay. In this quantity of the Gravel extraction amount in Pyay is not includes directly extracted by dredge boats to transfer to barges because Ministry orders ban on Gravel Mining at the time of the survey. One of the distributors said, in 2015 to 2016, one large Gravel extraction site/plot in 59 distributors are dredging around Pyay, Ayeyarwady River. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 10,000 to 15,000 kyats, Small Gravel is 25,000 to 30,000 kyats and Large Gravel is 45,000 to 50,000 kyats. For licensing, registration shall be done at DWIR, Mining Department and State/Division General Administration Department.

A total of three main distributors are engaged in construction sand mining from the Ayeyarwady River in Shwetaung. Sand extraction sites are located at the downstream of Shwetaung near Tet Thit Kyun of Ayeyarwady River (8 to 15 Gyins/~22 to 42 m^3) dragging boat by three to four times a day. Gravel extraction sites are located at Htan Lone Chaung village, Shwe Taung Myo Ma, Ayeyarwady River and they used (7 to 20 Gyins/~19 to 56 m^3) two dragging boats one time per day allows to extract from that sites. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 10,000 to 15,000 kyats, Small Gravel is 25,000 to 30,000 kyats and Large Gravel is 50,000 kyats. For licensing, registration shall be done at DWIR, Mining Department and State/Division General Administration Department. Annual maximum quantity of construction sand extraction is noticed approximates for ~92,960 m^3 and Gravel extraction ~15,282 m^3 is mined by Shwetaung.

A total of five main distributors are engaged in construction sand mining from the Ayeyarwady River in Zalon. Ministry orders ban on Sand and Gravel Mining around Zalon because of bank erosion. Gravel barges come from upstream of Hinthada, Moenyo, Kanaung, Myanaung Ayeyarwady River. Gravel distributors are closed for gravel in these months because they do not have gravel to sell. Sand distributors are getting sand from the sandbanks of Ayeyarwady River around the village of Zalon. When the survey is conducted, only two distributors are engaged in construction sand extracted/grabbed by shovel from the high sandbar/old sand deposited island form Ayeyarwady River upstream of Zalon. Daily extraction for construction sand is about (2 to 4 Gyins/~5 to 17 m^3) by small dragging boat two times a day. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 12,000 to 15,000 kyats and small Gravel is 25,000 to 30,000 kyats. For licensing, registration shall be done at DWIR, Mining Department and State/Division General Administration Department.

A total of three main distributors are engaged in construction sand mining from the Ayeyarwady River in Danabyu. Sand extraction sites are located at around Danabyu Ayeyarwady River, (8 to 15 Gyins/~22 to 42 m^3) dragging boat by 2 to 3 times a day. Gravel extraction sites are located upstream of Danabyu and they used (3 to 5 Gyins/~8 to 14 m^3) two dragging boats per one time per day allows to extract from that sites. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 6,000 to 7,000 kyats and Gravel is 70,000 kyats. For licensing, registration shall be done at DWIR, Mining Department and State/Division General Administration Department). Estimate of total number ~5 to 8 labourers are working in at the one sand distribution centres and 20 to 50 temporary labourers and 5 to 8 labourers are working in one boat at extraction sites in Pyay.

A total of three main distributors are engaged in construction sand mining from the Ayeyarwady River in Nyaungdone. Sand extraction sites are located at upstream of Nyaungdone and Sakaw village around Nyaungdone Ayeyarwady River, (20 Gyins/~56 m^3) dragging boat by two times a day. Gravel extraction sites are located at upstream of Nyaungdone, Htet Wa Gyi and Thabyu Ayeyarwady River and they used (30 Gyins/~85 m^3) one dragging boats per one time per day from that sites. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 7,000 kyats and Gravel is 70,000 kyats. For licensing, registration shall be done at DWIR, Mining Department and State/Division General Administration Department. Estimate of total number approximately five labourers are working in at the one sand distribution centres and seven to eight labourers are working in one boat at extraction sites in Nyaungdone.

Figure 1.2 Sand and Gravel Mining Survey sites in Pyay and Shwetaung

Ayeyarwady Delta (Hinthada, Zalon, Danubyu, and Nyaungdone)

A total of five main distributors are engaged in construction sand and gravel mining from the Ayeyarwady River in Hinthada. Sand extraction sites are located at the main channel of Hinthada, Ayeyarwady River at Phaung Seik, Kyone Lahar, Sein Tone, Nga Pyaw Taw, Oat Ywar Lay, and Phaung Kyaung area and they used (20 to 40 Gyins/~56 to 113 m^3) dragging boat by 2 to 4 times a day. Gravel extraction sites are located at ~8 to 10 miles upstream of Htein Taw, Moe Nyo Town, Ayeyarwady River. Extraction sites map designed by DWIR. The construction sand and coarse sand and gravel from Ayeyarwady River extracted was used locally for construction purposes. One of the main sand and gravel distributers sold river gravel and mountain gravel. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 5,000 to 7,000 kyats, coarse sand price is 10,000 kyats, and small to large gravel is 70,000 to 80,000 kyats. They operate with 5 to 10 permanent workers at distribution centres and temporary workers 40 to 100 in Hinthada.

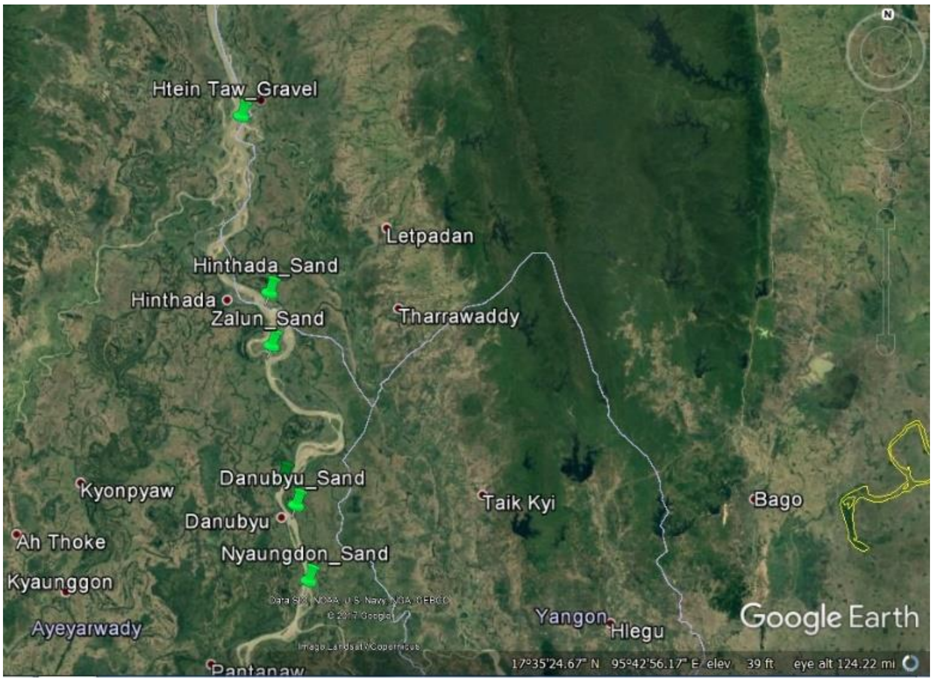

Figure 1.3 Sand and Gravel Mining Survey sites in Zalon, Danabyu, and Nyaungdon

Yangon

A total of 113 main distributors are engaged in construction sand and coarse sand mining from the Hlaing River, Yangon River, and Bago River in Yangon. Distribution centres located at Shwe Pyi Thar (36), Pazundaung and Tharkayta (8), Thanlyin and Thilawar (14), Thingangyun and North Dagon Myothit (9), Kamayut and Insein Ywarma (16), and Hlaing Thar Yar (30) in Yangon. Distribution centres sold gravel from the Ayeyarwady River, transported from extraction sites of Maggwe, Bago and Ayeyarwady Divisions by barges (~150 to 350Gyins/~425 to 990 m^3) to Yangon on average 2 to 3 times per two months. Gravel extraction sites were Michaung Ye, Kannma, Kyaw Swa (Maggwe Division), Pyay, Shwe Taung, Htone Bo, Moe Nyo, Htein Taw (Bago Division) and Myaung Aung, Kanaung, Shwe Kyin, Hinthada, Thone Sae Kyun (Ayeyarwady Division) at Ayeyarwady River.

The area of Shwe Pyi Tar, Sand extraction sites are located at the main channel of Hlaing River near Wartayar and more than 36 distributors used (25 to 80 Gyins/~70 to 226 m^3) dragging boat by 2 to 3 times a day. Extraction sites map designed by State/Division General Administration Department and survey by DWIR. Daily extraction for construction sand large operation is about (80 to 200 Gyins/~226 to 339 m^3), and small and medium are about (20 to 60 Gyins/~56 to 169 m^3). The construction sand and coarse sand from Hlaing River extracted was used locally for construction and Landfill purposes. Construction sand distributed to Shwe Pyi Thar Industrial Park, Mingalardon Industrial Park Shwe Pauk Kan Industrial park and occasionally distributed to Hlegu and Htauk Kyant areas in Northen District of Yangon. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 3,000 to 5,000 kyats, Coarse sand price is 6,000 to 8,000 kyats, Small to large Gravel is 50,000 to 100,000 kyats. They operate with total number 4 to 8 labourers are working in at the one sand distribution centres and 20 to 80 temporary labourers and 5 to 15 labourers are working in one boat at extraction sites in Shwe Pyi Thar. Most of all distribution centres used a mechanical wheel loader and they transport by light tracks. Two of the distributors had been transported construction sand (3,000 to 5,000 Gyins/~8,490 to 14,150 m^3) by pumping with long pipeline from the dredging boat to the Industrial sites within 3 to 5 months with special projects. Estimates of annual maximum quantity of construction sand extraction is noticed approximates for ~1,479,693 m^3 of sand is mined at Hlaing River, Shwe Pyi Thar. Approximates of annual volume of gravel ~157,205 m^3 is distributed by Shwe Pyi Thar area. Extraction is year-round, but operation is stopped only a few days when water level is high, especially during monsoon season (June, July, August, and September). Demand is highest in open seasons, but trend over the past ten years is highest and recent years start declining because of less construction and Ministry orders ban on Gravel Mining sites mid-June to August 2017 and not enough gravel to sell.

The area of Pazundaung and Tharkayta, Sand extraction sites are located at the main channel of at the joining area of Yangon River, Bago River and Pazundaung Creek and 8 distributors used (20 to 40 Gyins/~56 to 113 m^3) dragging boat by 1 to 2 times per day. Extraction sites map designed by State/Division General Administration Department and survey by DWIR. Daily extraction for construction sand large operation is about (20 to 40 Gyins/~56 to 113 m^3) and coarse sand (20 to 40 Gyins/~56 to 113 m^3) from Thilawar extracted was used locally for construction purposes. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 6,000 to 7,000 kyats, Coarse sand price is 7,000 to 8,000 kyats, Small to large Gravel is 80,000 to 95,000 kyats. They operate with total number 4 to 8 labourers are working in at the one sand distribution centres and 30 to 120 temporary labourers and 5 to 10 labourers are working in one boat at extraction sites in Thalawar. Most of all distribution centres used a mechanical wheel loader and they transport by light tracks. Estimates of annual maximum quantity of construction sand extraction is noticed approximates for ~123,954 m^3 of sand is mined at Yangon River, Thilawar. Approximates of annual volume of Gravel ~58,849 m^3 is distributed by Pazundaung and Tharkayta area. Sand Extraction is year-round, but operation is stopped only a few days when water level is high, especially during monsoon season (June, July, August, and September). Demand is highest in open seasons, but trend over the past four to five years is highest and recent years are regular. From last year 2016 decreased demand because of less construction and Ministry orders ban on Gravel Mining sites and Gravel price is higher and customers do not like the quality of small gravel.

The area of Thanlyin and Thilawar, Sand extraction sites are located at the main channel of at the joining area of Yangon River, Bago River near Thilawar and more than 14 distributors used (20 to 40 Gyins/~56 to 113 m^3) dragging boat by one time per day. Extraction sites map designed by State/Division General Administration Department and survey by DWIR. Daily extraction for construction sand large operation is about (20 to 40 Gyins/~56 to 113 m^3) and coarse sand (20 to 40 Gyins/~56- 113 m^3) from Thilawar extracted was used locally for construction purposes. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 6,000 to 7,000 kyats, Coarse sand price is 12000 kyats, Small to large Gravel is 80,000 to 100,000 kyats. They operate with total number 4 to 8 labourers are working in at the one sand distribution centres and 30 to 100 temporary labourers and 5 to 10 labourers are working in one boat at extraction sites in Thalawar. Most of all distribution centres used a mechanical wheel loader and they transport by light tracks. Estimates of annual maximum quantity of construction sand extraction is noticed approximates for ~356,228 m^3 of sand is mined at Yangon River, Thilawar. Approximates of annual volume of Gravel ~76,693 m^3 is distributed by Thanlyin and Thilawar, Tuntae, Khayan and Thonekwa area. Sand Extraction is year-round, but operation is stopped only a few days when water level is high, especially during monsoon season (June, July, August, and September). Demand is highest in open seasons, but trend over the past 6 years and Thilawar Industrial Park construction time is highest and recent years are regular. From this year decreased demand because of less construction and Ministry orders ban on Gravel Mining sites and Gravel price is higher and not enough gravel to sell.

The area of Thingangyun and North Dagon Myothit, Sand extraction sites are located at the main channel of at the joining area of Yangon River, Bago River near Thilawar and more than nine distributors used (18 to 60 Gyins/~50 to 169 m^3) dragging boat by one time per day. Sand extraction sites map designed by DWIR. Daily extraction for construction sand large operation is about (20 to 40 Gyins/~56 to 113 m^3) and coarse sand (20 to 40 Gyins/~56 to 113 m^3) from Thilawar extracted was used locally for construction purposes. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 6,000 to 7,000 kyats, Coarse sand price is 8,000 kyats, Small to large Gravel is 80,000 to 90,000 kyats. They operate with total number 4 to 8 labourers are working in at the one sand distribution centres and 20 to 30 temporary labourers and 5 to 10 labourers are working in one boat at extraction sites in Thalawar. Most of all distribution centres used a mechanical wheel loader and they transport by light tracks. Estimates of annual maximum quantity of construction sand extraction is noticed approximates for ~397,686 m^3 of sand is mined at Yangon River, Thilawar. Approximates of annual volume of Gravel ~31,385 m^3 is distributed by Thingangyun, North Dagon Myothit and Dagon Myothit Industrial Park area and Road construction. Sand Extraction is year-round, but operation is stopped only a few days when water level is high, especially during monsoon season (June, July, August, and September). Demand is highest in open seasons, but Ministry orders ban on Gravel Mining sites and Gravel price is higher and demand of sand is decreasing.

The area of Kamayut and Insein Ywarma, Sand extraction sites are located at the main channel of at the Hlaing River, Wartayar and more than 16 distributors used (17 to 30 Gyins/~48 to 85 m^3) dragging boat by 2 time per day. Extraction sites map designed by State/Division General Administration Department and survey by DWIR. Daily extraction for construction sand large operation is about (17 to 30 Gyins/~48 to 85 m^3) at Ywartayar and coarse sand (20 to 30 Gyins/~56 to 85 m^3) from Thilawar extracted was used locally for construction purposes. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 6,000 to 7,000 kyats, Coarse sand price is 8000 kyats, Small to large Gravel is 90,000 to 100,000 kyats. They operate with total number 4 to 8 labourers are working in at the one sand distribution centres and 10 to 50 temporary labourers and 5 to 10 labourers are working in one boat at extraction sites in Thilawar. Most of all distribution centres used a mechanical wheel loader and they transport by light tracks. Estimates of annual maximum quantity of construction sand extraction is noticed approximates for ~346,040 m^3 of sand is mined at Yangon River, Thilawar. Approximates of annual volume of Gravel ~62,374 m^3 is distributed by Kamayut, Insein Ywarma and Hlaing area. Sand Extraction is year-round, but operation is stopped only a few days when water level is high, especially during monsoon season (June, July, August, and September). Normally, demand is highest in open seasons, but Ministry orders ban on Gravel Mining sites and recently demand is decreased for sand and gravel demand.

The area of Hlaing Thar Yar, Sand extraction sites are located at the main channel of Hlaing River, Yangon River near Alone, Thilawar and Wartayar, more than 30 distributors used (20 to 30 Gyins/~56 to 85 m^3) dragging boat by 1 times a day. Hlaing Thar Yar distribution centres located at Pan Hlaing River, left bank of Shwe Pyi Thar Industrial Park No.4. Small Gravel barges (~100 to 200 Gyins/~424 to 566 m^3) only transported from the Gravel Mining site to enter with tide to Pan Hlaing River to the distribution centres. Extraction sites map designed by State/Division General Administration Department and survey by DWIR. Daily extraction for construction sand large operation is about (80 to 100 Gyins/~226 to 283m^3), and small and medium are about (20 to 40 Gyins/~56 to 113 m^3). The construction sand and coarse sand from Hlaing River extracted was used locally for construction purposes. Construction sand distributed to Hlaing Thar Yar Industrial Park, Shwe Lin ban Industrial Park, and Industrial Park Zones 1 to 4 and occasionally distributed to housing projects, Shwe Kan Thar Yar areas in Hlaing Thar Yar Township. Estimate of selling price shows that 1 Gyins/2.83 m^3 per construction sand price is 5,000 to 75,000 kyats, Coarse sand price is 13,000 kyats, Small to large Gravel is 90000 to 100,000 kyats. They operate with total number ~4 to 5 labourers are working in at the one sand distribution centres and 20 to 100 temporary labourers and 5 to 10 labourers are working in one boat at extraction sites. Most of all distribution centres used a mechanical wheel loader and they transport by light tracks. Estimates of annual maximum quantity of construction sand extraction is noticed approximates for ~864,000 m^3 of sand is mined at Hlaing River, Shwe Pyi Thar. Approximates of annual volume of Gravel ~86,685 m^3 is distributed by Hlaing Thar Yar area. Sand extraction is year-round, but operation is stopped only a few days when water level is high, especially during monsoon season (June, July, August, and September). Demand is highest in open seasons, but trend over the past ten years is highest and recent years start declining because of less construction and Ministry orders ban on Gravel Mining sites mid-June to August 2017 and not enough stock of gravel to distribute.

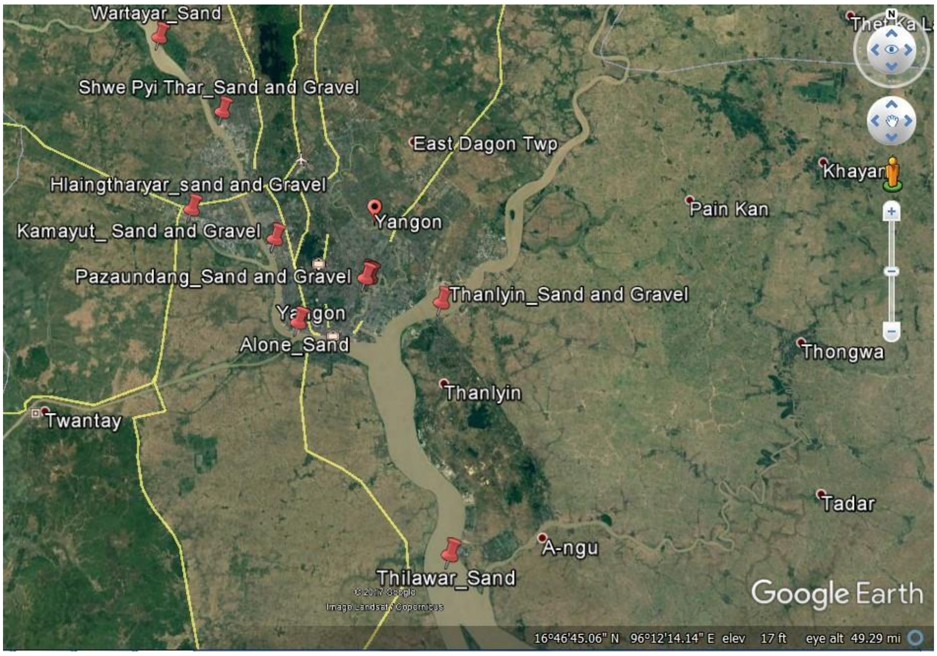

Figure 1.5 Sand and Gravel Mining Survey sites in Yangon

Figure 1.5a Photos of different Gravel sizes from Ayeyarwady River, Yangon

Figure 1.5b - Sand dredging boats and equipment operating on site in Yangon

Table 1.1 Locations of sand and gravel distribution centres

No	Date	Site	Region	Location	Distribution Centres	Latitude N	Longitude E
1	27 Aug	Site 1	Mandalay	Mayan Chan Seik	Zaw Ti Ka	21.9896	96.0615
2	27 Aug	Site 2	Mandalay	Mayan Chan Seik	Nyi Naung Khine Myal	21.9888	96.0610
3	27 Aug	Site 3	Mandalay	Chaw Seik	Lakabar	21.9610	96.0531
4	27 Aug	Site 4	Mandalay	Chaw Seik	Pyae Phyo Kyaw	21.9591	96.0524
5	27 Aug	Site 5	Mandalay	Chaw Seik	Shwe Yin Oo	21.9590	96.0523
6	27 Aug	Site 6	Mandalay	Chaw Seik	Thein Yadanar	21.9588	96.0523
7	27 Aug	Site 7	Mandalay	Chaw Seik	AAA	21.9587	96.0522
8	27 Aug	Site 8	Mandalay	Chaw Seik	Kaday Kyaw	21.9586	96.0522

No	Date	Site	Region	Location	Distribution Centres	Latitude N	Longitude E
9	27 Aug	Site 9	Mandalay	Chaw Seik	Kaung Kin Thar	21.9582	96.0520
10	27 Aug	Site 10	Mandalay	Chaw Seik	Moe Htet Ayeyar	21.9582	96.0520
11	27 Aug	Site 11	Mandalay	Chaw Seik	Shwe Gabar Moe	21.9580	96.0516
12	27 Aug	Site 12	Mandalay	Near New Sagaing Bridge	Shwe Min Thar	21.8822	96.0083
13	27 Aug	Site 13	Mandalay	Shwe Kyat Yat	Paing3	21.8822	96.0083
14	27 Aug	Site 14	Mandalay	Shwe Kyat Yat	Kaung Thant Kyaw	21.8822	96.0083
15	27 Aug	Site 15	Mandalay	Old MCDC Dumping site	Than Tayar	21.8867	96.0112
16	27 Aug	Site 16	Mandalay	Near MCDC Park	Khit Sar	21.8867	96.0112
17	27 Aug	Site 17	Mandalay	Pay Pin Seik	Shwe Myint Tun	21.9488	96.0501
18	27 Aug	Site 18	Mandalay	Pay Pin Seik	Aung Kyaw Zin	21.9487	96.0501
19	27 Aug	Site 19	Mandalay	Pay Pin Seik	Yadanarpon Aung Hein	21.8868	96.0110
20	27 Aug	Site 20	Mandalay	Pay Pin Seik	Yadanar	21.8868	96.0110
21	27 Aug	Site 21	Mandalay	Pay Pin Seik	Min Kyan Sitt	21.8865	96.0108
22	27 Aug	Site 22	Mandalay	Pay Pin Seik	Kung Kin Cho	21.8871	96.0108
23	27 Aug	Site 23	Mandalay	Pay Pin Seik	Kaung Su	21.8868	96.0107
24	27 Aug	Site 24	Mandalay	Pay Pin Seik	Sein Si Myint	21.8868	96.0107
25	27 Aug	Site 25	Mandalay	Shwe Kyat Yat	Ngwe Pyae Shan	21.8800	96.0036
26	27 Aug	Site 26	Mandalay	Shwe Kyat Yat	Khine Min	21.8800	96.0038
27	27 Aug	Site 27	Mandalay	Chaw Seik	Nan Ayeyar	21.9579	96.0518
28	27 Aug	Site 28	Mandalay	Chaw Seik	Nyein Chan Thar	21.9580	96.0517
29	27 Aug	Site 29	Mandalay	Chaw Seik	Tine Kyaw	21.9581	96.0520
30	27 Aug	S Site 1	Sagaing	Sagaing Kannar St	Shwe Min Han	21.8912	95.9977
31	27 Aug	S Site 2	Sagaing	Sagaing Kannar St	Khine Shwe War	21.8913	95.9979
32	27 Aug	S Site 3	Sagaing	Near Old Sagaing Bridge	Zabu Htun	21.8744	95.9876
33	27 Aug	Site 30	Mandalay	Mayan Chan Seik	Myittar Shin	21.9830	96.0596
34	27 Aug	Site 31	Mandalay	Mayan Chan Seik	Htwe Htwe Lay	21.9830	96.0595
35	27 Aug	Site 32	Mandalay	Mayan Chan Seik	Yamin	21.9830	96.0595
36	27 Aug	Site 33	Mandalay	Mayan Chan Seik	Ma Nwe Ni and Ko Thaw Myo	21.9830	96.0595
37	28 Aug	Site 1	Mandalay	Shwe Sar Yan Village	Ma Nyo (Thal Kwan Yar)	21.8390	96.2144
38	28 Aug	Site 2	Mandalay	Shwe Sar Yan Village	Sein Sein (Juice Corner)	21.8390	96.2148
39	28 Aug	Site 3	Mandalay	Shwe Sar Yan Village	U Aung San	21.8391	96.2148
40	28 Aug	Site 4	Mandalay	Shwe Sar Yan Village	Ko Naing Aung Win	21.8385	96.2133
41	2 Aug	Site 1	Yangon	Shwepyithar	Pyi Myanmar Aung	16.9324	96.0733
42	2 Aug	Site 2	Yangon	Shwepyithar	Chan Thar	16.9328	96.0729
43	2 Aug	Site 3	Yangon	Shwepyithar	Toe Tat Lin/2	16.9333	96.0730
44	2 Aug	Site 4	Yangon	Shwepyithar	Lin Myat	16.9328	96.0729
45	2 Aug	Site 5	Yangon	Shwepyithar	Khaing Thazin	16.9331	96.0729
46	2 Aug	Site 6	Yangon	Shwepyithar	Hlyan Htet Kyaw	16.9380	96.0682

No	Date	Site	Region	Location	Distribution Centres	Latitude N	Longitude E
47	2 Aug	Site 7	Yangon	Shwepyithar	Galone (2)	16.9380	96.0682
48	2 Aug	Site 8	Yangon	Shwepyithar	Yoon Nadi	16.9379	96.0683
49	2 Aug	Site 9	Yangon	Shwepyithar	999	16.9379	96.0684
50	2 Aug	Site 10	Yangon	Shwepyithar	Win Sandi	16.9381	96.0682
51	2 Aug	Site 11	Yangon	Shwepyithar	Lamin Aein	16.9380	96.0687
52	2 Aug	Site 12	Yangon	Shwepyithar	Soe San Win	16.9378	96.0738
53	2 Aug	Site 13	Yangon	Shwepyithar	Nadi Htun	16.9373	96.0687
54	2 Aug	Site 14	Yangon	Shwepyithar	Ye Yint Aung	16.9373	96.0687
55	2 Aug	Site 15	Yangon	Shwepyithar	Zaw (Ma Khine)	16.9373	96.0689
56	2 Aug	Site 16	Yangon	Shwepyithar	Kaung San	16.9373	96.0689
57	2 Aug	Site 17	Yangon	Shwepyithar	Aung Kaung Sat	16.9371	96.0692
58	2 Aug	Site 18	Yangon	Shwepyithar	RNO	16.9356	96.0705
59	2 Aug	Site 19	Yangon	Shwepyithar	Shwe Nawarat	16.9368	96.0694
60	2 Aug	Site 20	Yangon	Shwepyithar	Nilar Pearl	16.9349	96.0710

No	Date	Site	Region	Location	Distribution Centres	Latitude N	Longitude E
61	2 Aug	Site 21	Yangon	Shwepyithar	Miba Myitar	16.9427	96.0733
62	3 Aug	Site 22	Yangon	Shwepyithar	War War Win	16.9806	96.0389
63	3 Aug	Site 23	Yangon	Shwepyithar	Aung Phyo	16.9806	96.0390
64	3 Aug	Site 24	Yangon	Shwepyithar	Soe San	16.9794	96.0401
65	3 Aug	Site 25	Yangon	Shwepyithar	Naing	16.9792	96.0398
66	3 Aug	Site 26	Yangon	Shwepyithar	Tun Myittar	16.9786	96.0407
67	3 Aug	Site 27	Yangon	Shwepyithar	War War Win 2	16.9737	96.0465
68	3 Aug	Site 28	Yangon	Shwepyithar	War War Win 1	16.9731	96.0472
69	3 Aug	Site 29	Yangon	Shwepyithar	Pho Chon	16.9737	96.0465
70	3 Aug	Site 30	Yangon	Shwepyithar	Zwal Mann 1	16.9391	96.0675
71	3 Aug	Site 31	Yangon	Shwepyithar	U Moe Gyi 2	16.9386	96.0680
72	3 Aug	Site 32	Yangon	Shwepyithar	Aung	16.9396	96.0671
73	3 Aug	Site 33	Yangon	Shwepyithar	Ngwe Lwin Oo	16.9403	96.0658
74	3 Aug	Site 34	Yangon	Shwepyithar	Shwe Wah Htun	16.9400	96.0656
75	3 Aug	Site 35	Yangon	Shwepyithar	Kyi Linn Thein	16.9222	96.0798
76	3 Aug	Site 36	Yangon	Shwepyithar	Aung Htet Lin	16.9401	96.0668
77	4 Jul	Site 37	Yangon	Pazundaung	Swe Ein Taw	16.8042	96.1853
78	4 Aug	Site 38	Yangon	Pazundaung	Wanna Aung	16.8044	96.1852
79	4 Aug	Site 39	Yangon	Pazundaung	Shwe Thiha	16.8057	96.1886
80	4 Aug	Site 40	Yangon	Pazundaung	Pyi Myanmar	16.8086	96.1878
81	4 Aug	Site 41	Yangon	Tharkayta	Kaung Myat San	16.8092	96.1881
82	4 Aug	Site 42	Yangon	Tharkayta	Shwe Paing	16.8068	96.1867
83	4 Aug	Site 43	Yangon	Tharkayta	Myittar Mon	16.8069	96.1865
84	4 Aug	Site 44	Yangon	Tharkayta	Kyan Dine Aung	16.8079	96.1867
85	5 Aug	Site 45	Yangon	Than Lyin	Sein Hnin Si	16.8144	96.2831
86	5 Aug	Site 46	Yangon	Thilawa	Thilawa Navy Compound	16.6872	96.2335
87	5 Aug	Site 47	Yangon	Thilawa	Shwe Pyi Aye	16.6743	96.2430
88	5 Aug	Site 48	Yangon	Than Lyin	Myanmar Winner	16.7870	96.2499
89	5 Aug	Site 49	Yangon	Than Lyin	Myanmar Winner 2	16.7865	96.2494
90	5 Aug	Site 50	Yangon	Than Lyin	Ko Zaw	16.7870	96.2499
91	5 Aug	Site 51	Yangon	Than Lyin	Kaung Thazin Hein	16.7857	96.2492
92	5 Aug	Site 52	Yangon	Than Lyin	Shwe Myanmar	16.7866	96.2487
93	5 Aug	Site 53	Yangon	Than Lyin	U Aye Po	16.7863	96.2488
94	5 Aug	Site 54	Yangon	Than Lyin	777	16.7859	96.2490

No	Date	Site	Region	Location	Distribution Centres	Latitude N	Longitude E
95	5 Aug	Site 55	Yangon	Than Lyin	U Hla + Daw Amar Kyi	16.7861	96.2463
96	5 Aug	Site 56	Yangon	Than Lyin	Shin Thant Maung	16.7861	96.2458
97	5 Aug	Site 57	Yangon	Than Lyin	Hein Myittar	16.7852	96.2451
98	5 Aug	Site 58	Yangon	Than Lyin	Wah Lu Aung	16.7850	96.2448
99	5 Aug	Site 59	Yangon	Thingangyun	Min Khant Aung/Aung	16.7851	96.2448
100	5 Aug	Site 60	Yangon	Thingangyun	Myint Myat Aung	16.8159	96.2497
101	5 Aug	Site 61	Yangon	North Dagon	Dragon74	16.8565	96.1970
102	5 Aug	Site 62	Yangon	North Dagon	Ba La	16.8561	96.1951
103	5 Aug	Site 63	Yangon	North Dagon	Kyan Tine Aung	16.8560	96.1951
104	5 Aug	Site 64	Yangon	North Dagon	Thein	16.8556	96.1922
105	5 Aug	Site 65	Yangon	North Dagon	Win Ohn Shin	16.8557	96.1923
106	5 Aug	Site 66	Yangon	North Dagon	Htun	16.8558	96.1927
107	5 Aug	Site 67	Yangon	North Dagon	Moe Kyal Sin	16.8587	96.1882
108	6 Aug	Site 68	Yangon	Kamayut	U Htun Wai	16.8327	96.1140
109	6 Aug	Site 69	Yangon	Kamayut	Yadanarbon	16.8357	96.1121
110	6 Aug	Site 70	Yangon	Kamayut	Zabu Lin	16.8354	96.1125
111	6 Aug	Site 71	Yangon	Kamayut	Aung Thait Hti	16.8354	96.1125
112	6 Aug	Site 72	Yangon	Kamayut	Yar Thet Pan	16.8356	96.1127
113	6 Aug	Site 73	Yangon	Kamayut	Moe Myint Kyal	16.8358	96.1128
114	6 Aug	Site 74	Yangon	Kamayut	Aung Zabu	16.8362	96.1128
115	6 Aug	Site 75	Yangon	Kamayut	U Maw Si	16.8360	96.1131
116	6 Aug	Site 76	Yangon	Insein Ywar Ma	Aung Phyo Kyaw 2	16.8958	96.0892
117	6 Aug	Site 77	Yangon	Insein Ywar Ma	Aung Phyo Kyaw 1	16.8959	96.0892
118	6 Aug	Site 78	Yangon	Insein Ywar Ma	Yadanar Win	16.8937	96.0890
119	6 Aug	Site 79	Yangon	Insein Ywar Ma	Ayeyarwady	16.8939	96.0888
120	6 Aug	Site 80	Yangon	Insein Ywar Ma	Yadanar	16.8949	96.0885

No	Date	Site	Region	Location	Distribution Centre	Latitude N	Longitude E
61	2 Aug	Site 21	Yangon	Shwepyithar	Miba Myitar	16.9427	96.0733
62	3 Aug	Site 22	Yangon	Shwepyithar	War War Win	16.9806	96.0389
63	3 Aug	Site 23	Yangon	Shwepyithar	Aung Phyo	16.9806	96.0390
64	3 Aug	Site 24	Yangon	Shwepyithar	Soe San	16.9794	96.0401
65	3 Aug	Site 25	Yangon	Shwepyithar	Naing	16.9792	96.0398
66	3 Aug	Site 26	Yangon	Shwepyithar	Tun Myittar	16.9786	96.0407
67	3 Aug	Site 27	Yangon	Shwepyithar	War War Win 2	16.9737	96.0465
68	3 Aug	Site 28	Yangon	Shwepyithar	War War Win 1	16.9731	96.0472
69	3 Aug	Site 29	Yangon	Shwepyithar	Pho Chon	16.9737	96.0465
70	3 Aug	Site 30	Yangon	Shwepyithar	Zwal Mann 1	16.9391	96.0675
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75	3 Aug	Site 35	Yangon	Shwepyithar	Kyi Linn Thein	16.9222	96.0798
76	3 Aug	Site 36	Yangon	Shwepyithar	Aung Htet Lin	16.9401	96.0668
77	4 July	Site 37	Yangon	Pazundaung	Swe Ein Taw	16.8042	96.1853
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89	5 Aug	Site 49	Yangon	Than Lyin	Myanmar Winner 2	16.7865	96.2494
90	5 Aug	Site 50	Yangon	Than Lyin	Ko Zaw	16.7870	96.2499
91	5 Aug	Site 51	Yangon	Than Lyin	Kaung Thazin Hein	16.7857	96.2492
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93	5 Aug	Site 53	Yangon	Than Lyin	U Aye Po	16.7863	96.2488
94	5 Aug	Site 54	Yangon	Than Lyin	777	16.7859	96.2490
95	5 Aug	Site 55	Yangon	Than Lyin	U Hla + Daw Amar Kyi	16.7861	96.2463
96	5 Aug	Site 56	Yangon	Than Lyin	Shin Thant Maung	16.7861	96.2458
97	5 Aug	Site 57	Yangon	Than Lyin	Hein Myittar	16.7852	96.2451
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114	6 Aug	Site 74	Yangon	Kamayut	Aung Zabu	16.8362	96.1128
115	6 Aug	Site 75	Yangon	Kamayut	U Maw Si	16.8360	96.1131
116	6 Aug	Site 76	Yangon	Insein Ywar Ma	Aung Phyo Kyaw 2	16.8958	96.0892
117	6 Aug	Site 77	Yangon	Insein Ywar Ma	Aung Phyo Kyaw 1	16.8959	96.0892
118	6 Aug	Site 78	Yangon	Insein Ywar Ma	Yadanar Win	16.8937	96.0890
119	6 Aug	Site 79	Yangon	Insein Ywar Ma	Ayeyarwady	16.8939	96.0888
120	6 Aug	Site 80	Yangon	Insein Ywar Ma	Yadanar	16.8949	96.0885

No	Date	Site	Region	Location	Distribution Centres	Latitude N	Longitude E
121	6 Aug	Site 81	Yangon	Insein Ywar Ma	May	16.8951	96.0887
122	6 Aug	Site 82	Yangon	Insein Ywar Ma	Bhone Pyay Sone	16.8958	96.0892
123	6 Aug	Site 83	Yangon	Insein Ywar Ma	Aba Aung	16.8958	96.0892
124	19 Aug	Site 84	Yangon	Hlaing Thar Yar	Aung Su Kyaw 3	16.8610	96.0399
125	19 Aug	Site 85	Yangon	Hlaing Thar Yar	Ngwe Myint Mo	16.8610	96.0347
126	19 Aug	Site 86	Yangon	Hlaing Thar Yar	Kyal Sin Hein	16.8596	96.0438
127	19 Aug	Site 87	Yangon	Hlaing Thar Yar	Htoo Htet Thar	16.8595	96.0440
128	19 Aug	Site 88	Yangon	Hlaing Thar Yar	Pyay Kyaw	16.8595	96.0441
129	19 Aug	Site 89	Yangon	Hlaing Thar Yar	Sin Thone Kaung	16.8609	96.0377
130	19 Aug	Site 90	Yangon	Hlaing Thar Yar	Mahar Moe Hti	16.8610	96.0373
131	19 Aug	Site 91	Yangon	Hlaing Thar Yar	KTA	16.8608	96.0388
132	19 Aug	Site 92	Yangon	Hlaing Thar Yar	Han Thar Aung	16.8608	96.0389
133	19 Aug	Site 93	Yangon	Hlaing Thar Yar	Kyal Sin Hein	16.8607	96.0393
134	19 Aug	Site 94	Yangon	Hlaing Thar Yar	Myint Mo	16.8606	96.0395
135	19 Aug	Site 95	Yangon	Hlaing Thar Yar	Htun Tauk	16.8604	96.0404
136	19 Aug	Site 96	Yangon	Hlaing Thar Yar	Kyaw Kyaw Min	16.8603	96.0408
137	19 Aug	Site 97	Yangon	Hlaing Thar Yar	Htin Lin Aung	16.8603	96.0410
138	19 Aug	Site 98	Yangon	Hlaing Thar Yar	Ko Aung Thu	16.8596	96.0435
139	19 Aug	Site 99	Yangon	Hlaing Thar Yar	Pyi Kyaw	16.8610	96.0370
140	19 Aug	Site 100	Yangon	Hlaing Thar Yar	Shwe Ton Tae	16.8594	96.0445
141	19 Aug	Site 101	Yangon	Hlaing Thar Yar	Aung Myita	16.8592	96.0450
142	19 Aug	Site 102	Yangon	Hlaing Thar Yar	Myittar Moe (2)	16.8593	96.0437
143	19 Aug	Site 103	Yangon	Hlaing Thar Yar	Pyi Moe	16.8588	96.0452
144	19 Aug	Site 104	Yangon	Hlaing Thar Yar	Aung Moe Hein	16.8580	96.0475
145	19 Aug	Site 105	Yangon	Hlaing Thar Yar	Aung Phyo	16.8576	96.0481
146	19 Aug	Site 106	Yangon	Hlaing Thar Yar	Thein Than	16.8566	96.0494
147	19 Aug	Site 107	Yangon	Hlaing Thar Yar	Myit Tar Moe	16.8568	96.0491
148	19 Aug	Site 108	Yangon	Hlaing Thar Yar	Htin Lin Aung	16.8560	96.0501
149	19 Aug	Site 109	Yangon	Hlaing Thar Yar	Kyaw	16.9245	96.0731
150	19 Aug	Site 110	Yangon	Hlaing Thar Yar	Ayeyarwady	16.9161	96.0763
151	19 Aug	Site 111	Yangon	Hlaing Thar Yar	Yadanarbon	16.9141	96.0768
152	19 Aug	Site 112	Yangon	Hlaing Thar Yar	Thein Than Kyaw		
153	19 Aug	Site 113	Yangon	Hlaing Thar Yar	Htun		
154	11 Aug	Site 1	Ayeyarwady	Hinthada	Htay Aung Kyaw	17.6411	95.4896
155	12 Aug	Site 2	Ayeyarwady	Hinthada	Hnin Thazin	17.6385	95.4768
156	12 Aug	Site 3	Ayeyarwady	Hinthada	Aung Da Na		
157	12 Aug	Site 4	Ayeyarwady	Hinthada	Mya Nadi		
158	12 Aug	Site 5	Ayeyarwady	Hinthada	Tiger		
159	13 Aug	Site 1	Ayeyarwady	Zalon	Shwe Nadi	17.4811	95.5659
160	13 Aug	Site 2	Ayeyarwady	Zalon	Miba Myitar	17.4811	95.5659
161	13 Aug	Site 3	Ayeyarwady	Zalon	Ko Maung Nge	17.4811	95.5658
162	13 Aug	Site 4	Ayeyarwady	Zalon	U Aung Myo	17.4826	95.5638
163	13 Aug	Site 5	Ayeyarwady	Zalon	Ko Thaung Naing (Miba Myitta)		
164	13 Aug	Site 6	Ayeyarwady	Zalon	Ko Myo Gyi		
165	13 Aug	Site 7	Ayeyarwady	Zalon	Ko Maung Maung		
166	13 Aug	Site 8	Ayeyarwady	Zalon	Ko Nyunt Hlaing		
167	13 Aug	Site 9	Ayeyarwady	Zalon	Ko Kalar + Daw Aye Thwe		
168	13 Aug	Site 1	Ayeyarwady	Danubyu	Kaung Myat	17.2551	95.5949
169	13 Aug	Site 2	Ayeyarwady	Danubyu	Danabyu 2	17.2551	95.5950
170	13 Aug	Site 3	Ayeyarwady	Danubyu	Danabyu 3	17.2553	95.5951

No	Date	Site	Region	Location	Distribution Centres	Latitude N	Longitude E
171	13 Aug	Site 4	Ayeyarwady	Danubyu	Danabyu 4		
172	13 Aug	Site 5	Ayeyarwady	Danubyu	Danabyu 5		
173	13 Aug	Site 1	Ayeyarwady	Nyaung Done	Aung Htet Lin	16.9798	95.7356
174	13 Aug	Site 2	Ayeyarwady	Nyaung Done	Daw Thi		
175	13 Aug	Site 3	Ayeyarwady	Nyaung Done	Kyal Sin Lat		
176	17 Aug	Site 1	Bago	Pyay	Kan Htoo	18.8122	95.2154
177	17 Aug	Site 2	Bago	Pyay	Nay La	18.8375	95.2213
178	17 Aug	Site 3	Bago	Pyay	TK	18.8370	95.2214
179	17 Aug	Site 4	Bago	Pyay	Ko Than Zaw Oo	18.8347	95.2205
180	17 Aug	Site 5	Bago	Pyay	Win Nyi Naung	18.8472	95.2204
181	18 Aug	Site 1	Bago	Shwe Taung	Min Than Htike	18.7177	95.2073
182	18 Aug	Site 2	Bago	Shwe Taung	Shwe Wah Win	18.7120	95.2065
183	18 Aug	Site 3	Bago	Shwe Taung	Aung Zabu	18.7278	95.2127

ANNEX 5 - CM REPORT AND SUMMARY OF SEDIMENT MONITORING SITES AND RESULTS BY GEOMORPHIC ZONE

Ayeyarwady CM Image Report

Specific method of sampling

- One of the main challenges was to select representative locations at the site and zone scales. First, sampling was implemented inside the active tract of the river, on fresh bars, fresh sand deposits on islands margins, and channel bed. Samples were also collected in consolidated cross-sections opened by the lateral erosion of the river into vegetated islands, in order to compare fresh and undated older sediment, also called eroded banks in the comment. A total of four types of sites were required. This typology was maintained along the river continuum, from the headwaters to the lower course of the Ayeyarwady, and was tested on some tributaries.
- A complete understanding of the river functioning would require a wider effort, including, for instance, sampling inside ancient islands and former arms partly or totally disconnected from the present active tract.

Specific approach for understanding river functioning

- The reasons for selecting specific sites inside the active tract are related to the purpose of the aspect of the study, which is to understand river functioning. In general, a CM graph provides an image composed of a collection of points. River processes are deduced from the position of individual CM points in the graph, with one point per sample. A general model (or image) for rivers of the world exists, but each river and each particular reach inside a unique river displays its own signature and reveals specific types of hydromorphological functioning.
- It is the reason why the CM images are presented at the zone scale, including all the individual sampling sites. The sites were selected for their ability to represent characteristic fluvial landforms and processes operating in the active tract.

    1. Sediment originating from uniform suspension (i.e. non-turbulent water) were absent in the deposits. The other deposits originate from non-inundated sites during the period of survey.
    2. The image units determined by their position in the graphs mostly originate from a process called graded suspension (QR segment). A QR segment is parallel to the C = M line. Sediment was deposited by turbulent flow, usually during the recession of a flood). The size of sediment deposited by suspension varies according to river discharge and river energy. Turbulent flow is able to transport sand in suspension; the size of sand grains varies according to water depth. Values named respectively Cs+ and Cs- provide the size of the coarser and finer grain-sizes deposited in each individual site. From experience and considering the specific functioning of this river, it is considered that the coarsest value of C in the GS (Cs+) is comprised between 600 and 800 microns. The higher value of C in a sand deposit allows classifying it in the PQ segment.[5]
    3. The units deposited both by suspension and rolling (S+R) on the bed (PQ segment) are widely represented. The results pointing in PQ segment are parallel to the ordinate line (changing values of C are dominant). These processes explain some emergent bars and characterize channel deposits.

[5] Value of Cs is lower in the Mississippi at Mayersville (400 to 450 microns) due to lower turbulence (Passega and Byramjee, 1969).

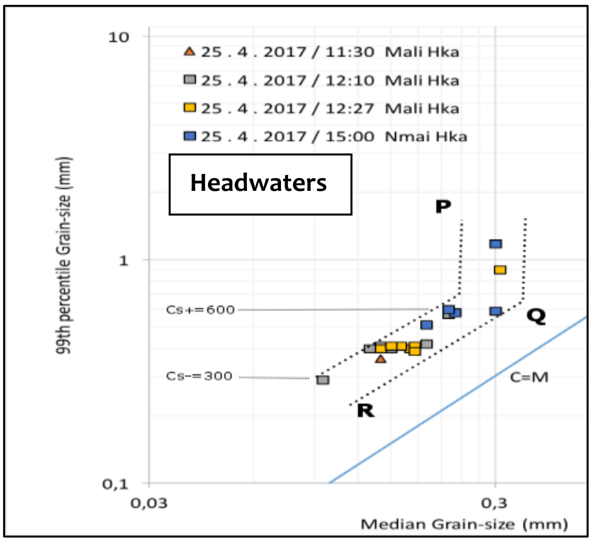
4. Some of the samples point in the OP segment, i.e. in the area of particles rolled on the channel bottom (pure process).
5. Several CM points do not belong to pure processes of deposition, as present in the area of tractive flows in the classical CM image. They originate from the mixture of two or more types of processes. This mixed composition may be most informative. Mixtures of GS and finer grains are considered, as well as mixtures of S+R and finer sediment, such as granules and sand.
6. Sediment is considered as well sorted when a QR segment points close to the C = M line; it is poorly sorted when grains are dispersed, with part of them being further from the C = M line.

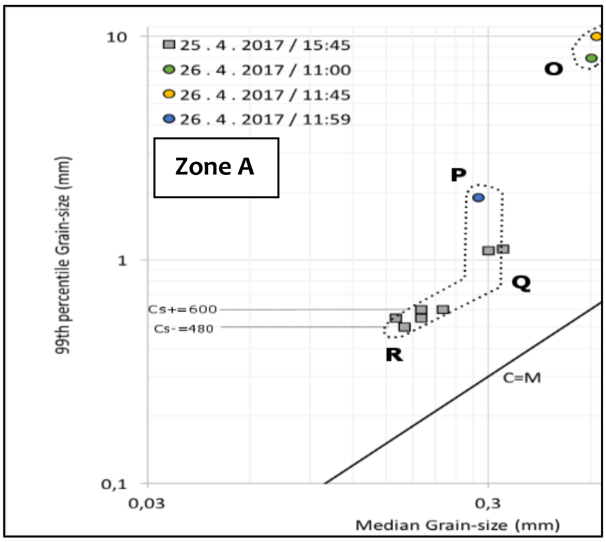
- The CM images may be compared along the river continuum to assess the upstream-downstream variability of river functioning.

Analytic results of the functioning of the river active tract at the zone and site scales

Zone headwaters (figure below) — The lower banks of the rivers display reddish coarse cobbles (40 to 50 cm in diameter); they are stable and may derive from ancient quaternary deposits. Cross-sections exposed by the lateral erosion of bars along the N'mai Hka alternate sorted sand and gravel. The headwater zone includes four sampling sites selected along the downstream reaches of the Mali Hka and N'mai Hka (sandbars).

1. Two coarse samples from the Mali Hka and N'mai Hka deposits (25/4/2017, 12:10 a.m. and 25/4/2017, 27:10 a.m.). They are located in segment PQ, and may be considered as mixtures of graded suspension and particles rolled from the channel bottom (R). The topography of the bed and bars allowed the rolling of coarse sand during the flood.
2. Most of the samples are made of sand and belong to segment QR. They originate from well-sorted graded suspension. The three sets of samples located in segment QR (referring to three different bars) differ by the value of C (an indicator of maximum turbulence), i.e. one bar at 600 microns and two bars at 400 microns.



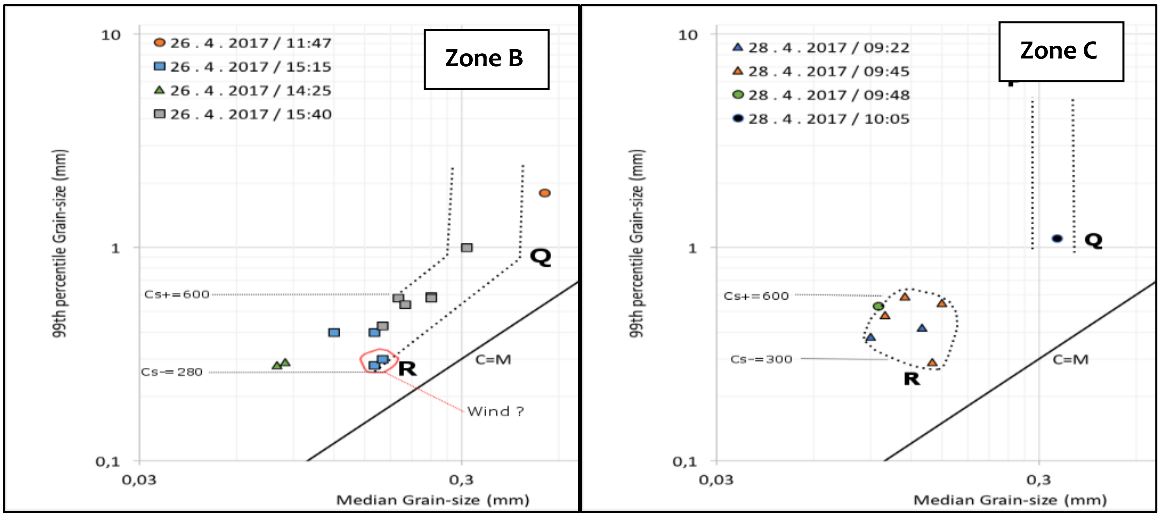


Zone A (figure above) — This zone displays low lateral bars of gravels (10 to 15 cm in diameter at least); some are ancient (reddish) and others are recent. Present data include three channel samples and a transect across top of a sandbar.

1. The channel was sampled (26/4/2017, 11:00 to 11:45 and 11:59); the three samples point as small gravel transported as rolled particles (segment ON). Another individual sample points in segment PQ.
2. The sampled sandbar is a lateral bar protected by bushy vegetation. It displays well-sorted and homogeneous sediment from graded suspension (QR segment). Grain-size has values of C comprised between 600 and 480 microns. Part of the sediment collected on a sandbar is a mix of S+R (PQ segment).

Zone B (figure below) — In this zone, three different types of sites were sampled, i.e. from two transects across distinct mid-stream bars, displaying sand from graded suspension (QR segment), one channel deposit, and one sample from an eroded bank.

1. One sample, located in a channel bed, belongs to segment R.
2. The coarsest sandbar is located in a wide channel; one of its samples pertains to segment PQ (26/4/2017, 3:40 p.m.). C values are comprised between 400 and 600 microns.
3. The site with finer deposits (26/4/2017, 3:15 p.m.) is located in the convexity of an active secondary channel (one of its samples is poorly sorted but two samples are very well sorted). C values are comprised between 280 and 400 microns.
4. Two samples from an eroded bank display a poor sorting; they may be a mix of fine-graded suspension and finer sand (a layer with low velocity or trapping by vegetation). C values are comprised of 280 microns. It is possible that this sediment was deposited by uniform suspension (segment RS of the CM graph) and that vegetation may have contributed to trapping silt. The reddish colour of the deposit could be explained by deposition of reddish silt originating from soil erosion.

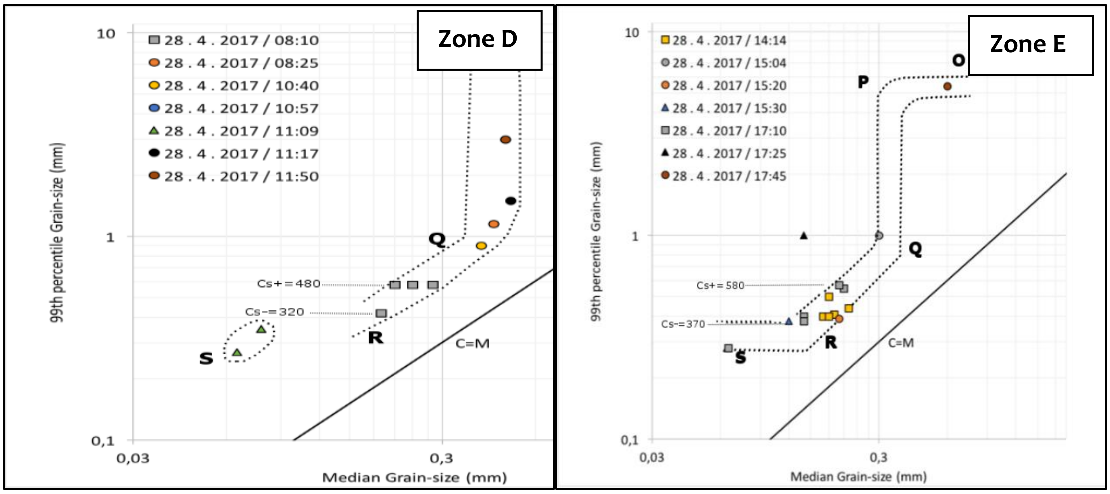


Zone C (figure above) — Two samples were collected in the channel, while the other ones were collected in eroded banks downstream of a gorge, in a widening reach.

1. Amongst the channel samples (28/4/2017, 9:22 and 10:05), one is composed of coarse sand, probably deposited after the flood peak over the coarser material. The other one, composed of poorly sorted sand, originates from graded suspension. It was enriched in finer material during the flood recession.
2. The eroded banks display horizontal layers of pink sand sediment. They are made mostly of poorly sorted graded suspension, possibly due to trapping of finer particles by vegetation. Values of C are comprised between 300 and 600 microns.

Zone D (figure below) — This zone displays well-sorted sediment, fitting very well with the classical CM image processes.

1. The samples from the channel point distinctively in segment PQ. They range from sand with some granules, to coarser and well-sorted gravel. They are probably deposited over a coarser lag of gravel.
2. A sandbar is composed of well-sorted sediment from graded suspension, with values of C comprised between 320 and 480 microns (28/4/2017, 10:40).
3. An eroded bank (28/4/2017, 11:09) is composed of stained poorly sorted sand (fine GS enriched in finer sand induces a low value of M). It may derive from uniform suspension, due to the trapping effect of vegetation.



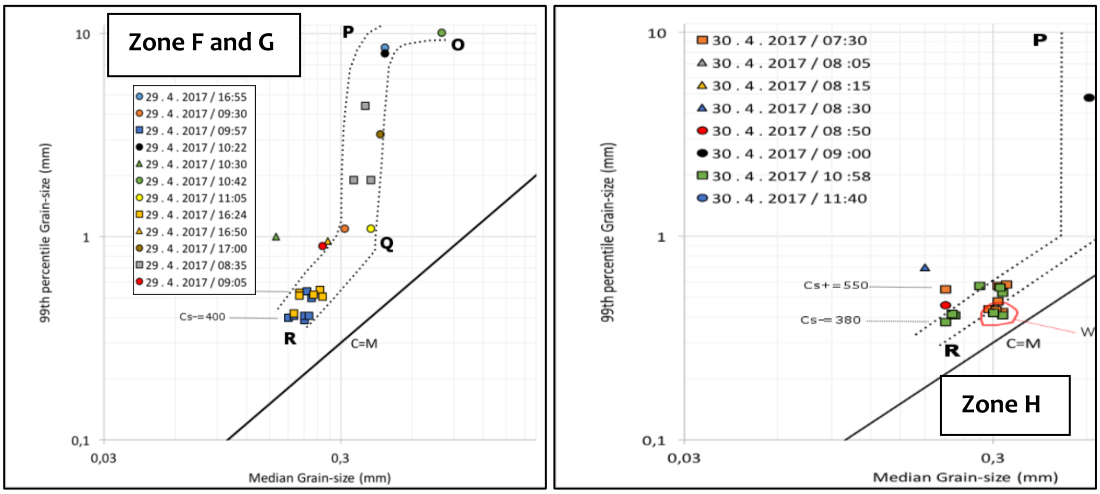
Zone E (figure above) — This zone has well-sorted sediment fitting with CM processes, as in zone D.

1. Two bed samples are composed: one of fine gravel, the other one of coarse sand (PQ segment). A third bed sample is composed of GS. All were redeposited on the channel bottom after the last flood.
2. Two sandbars were sampled (28/4/2017, 2:14 p.m. and 28/4/2017, 5:10 p.m.). They display a homogeneous sand deposited by graded suspension (QR segment). C values are comprised between 280 and 470 microns.
3. Two samples were located in eroded banks, and are a mixture of sand and finer particles (one from GS, the other one from GS + R). The low value at 280 microns may indicate a uniform suspension.

Zone F and G (figure below) — This zone displays characteristic well-sorted deposits from rolling (O), mixed rolling and GS, and pure GS.

1. The channel deposits are very significant. The coarsest one belongs to segment OP, and five others belong to segment PQ (mix of graded suspension and rolled particles, with different values of C explaining the position along the vertical segment). Particles belonging to segment PQ were sampled on a bar; being a mix of sand from graded suspension and rolled granules, they were probably transported as bedload and as GS along an inclined plane, emerging during the survey despite its elevation.

2. Two sandbars located on the side of the channel were sampled (29/4/2017, 9:57 a.m. and 29/4/2017, 4:24 p.m.). They were built up by pure well-sorted GS with C values comprised between 450 and 380 microns, from the bottom to the uppermost part of the bar. It may be interpreted by the fact that when flood recedes, the velocity remains strong. Some samples from another bar display a mix of rolled and suspended particles (29/4/2017, 8:35 a.m.).
3. At least two samples from eroded banks display the same C values as samples belonging to the PQ segment, but they have a lower value of the median M because the deposits trapped finer suspended load (29/4/2017, 10:30 a.m. and 29/4/2017, 4:50 p.m.).

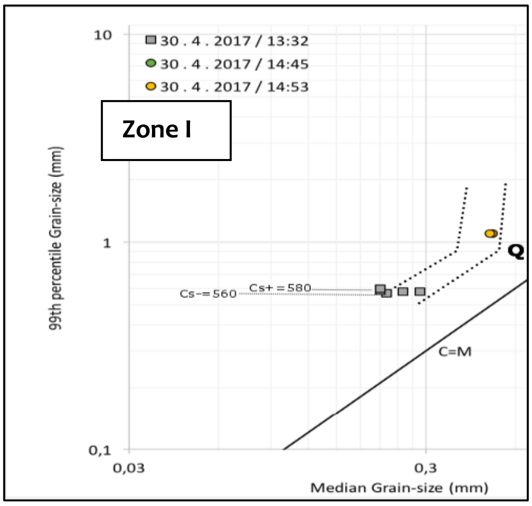


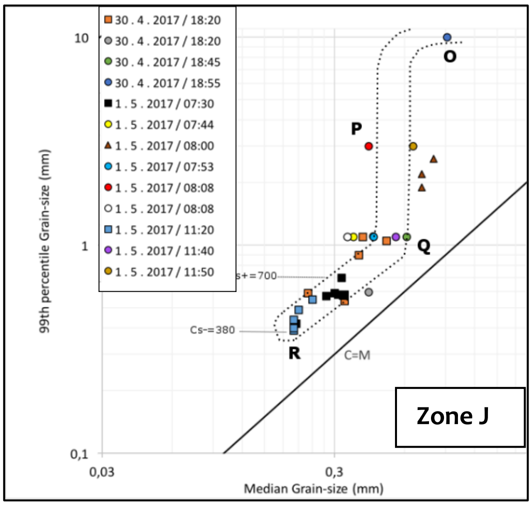
Zone H (figure above) — Eight samples or sets were used to qualify zone H processes.

1. Two channel samples correspond respectively to OP and PQ segments (30/4/2017, 9:00 a.m. and 30/4/2017, 10:30 a.m.). The sediment is similar to some coarse sediment from eroded banks (30/4/2017, 8:05 a.m. and 30/4/2017, 8:15 a.m.). Another bed sample originates from graded suspension processes; it was redeposited after the flood, probably over coarser particles.
2. Two sandbars, located on the soft bank of a sandy island, display characteristic well-sorted sand from GS (QR segment) with values of C comprised between 480 and 280 microns (30/4/2017, 7:30 a.m. and 30/4/2017, 10:58 a.m.). Two or three samples are very close to the CM line of perfect sorting. These samples could be influenced by wind sorting.
3. A third sample from an eroded bank (30.4.2017, 8:30 a.m.) is a poorly sorted and coarse deposit from graded suspension, enriched in trapped finer particles.

Zone I (figure below) — This zone is a large bar bordered by a vegetated swale.

1. Bed samples (30/4/2017, 2:45 and 2:53 p.m.) belong to the finer values of segment PQ (C value is close to 1 mm).
2. A sandbar (30/4/2017, 2:53 p.m.) originates from graded suspension (QR segment); the C values are quite high, at 560 to 580 microns.





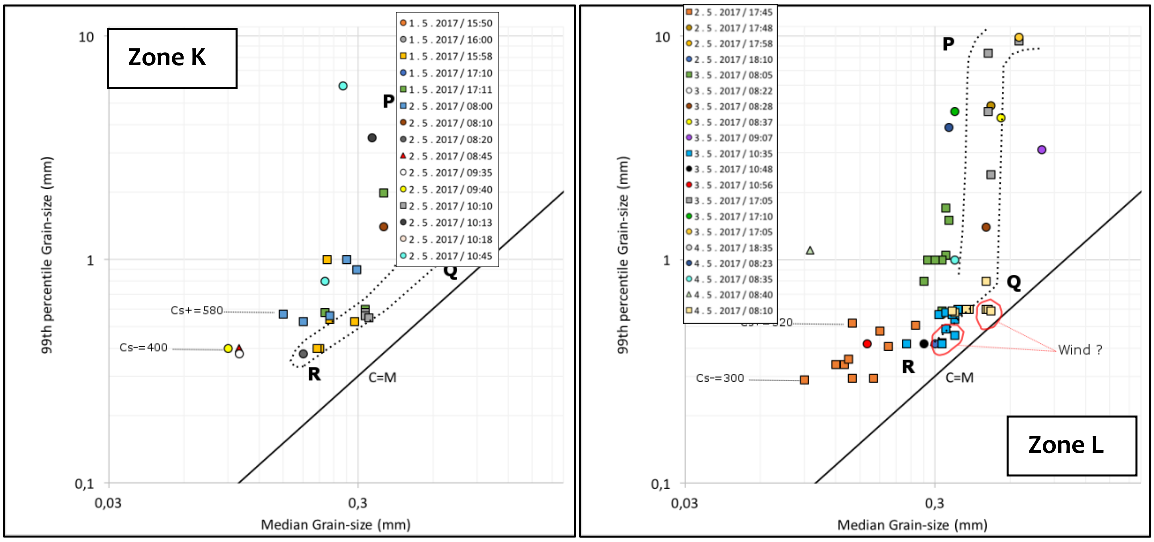
Zone J (figure above) — The effort of sampling was important in this zone. Moreover, the reach displays ancient lateral bars with well-sorted small gravel and a crisscrossed internal structure (ancient braiding).

1. Nine samples were collected in the channel in nine different places. One sample belongs to segment OP (rolling), six to the lower part of segment PQ (GS including rolled coarse sand), and one is very well-sorted sand from GS (QR segment) redeposited at the end of the flood or after. This picture underlines the probable role of post-floods processes in the shaping of sandy landforms.
2. Three sandbars were sampled. Two bars (1/5/2017, 7:30 and 11:20 a.m.) are composed of pure well-sorted graded suspension (QR segment) with C values between 280 and 700 microns. However, one of them (1/5/2017, 6:20), with a C value influenced by coarse sand, is comprised in the QP segment type. In this case, the GS sand is in the upper part of graded suspension deposits, i.e. influenced by a rather high turbulence.
3. Three samples were collected in an eroded bank (1/5/2017, 8:00). They look like samples from PQ processes but with a better sorting, as they are closer to the CM line than the pure QP samples.

Zone K (figure below) — Sampling in this zone was done across flat bars. The complex CM image reflects a combination of pure CM processes and of mixed processes in backwaters upstream of the confluence with the Chindwin River.

1. Nine samples originate from the channel bed and altogether display a scattered pattern with a wide range of M values. Five samples belong to the PQ segment, and three of them to graded suspension, with the lower values of GS at 300 microns. Two of them (2/5/2017, 9:35 and 9:40) are mixed with finer material (C is constant at 300 microns but M varies with values at about 100 microns). These last three sand samples belong to a kind of sediment redeposited on the channel bottom after a flood.
2. Four sandbars were also sampled. All of them are issued from graded suspension (QR segment) with a medium turbulence (C value at 600 to 380 microns); and all of them have a coarser component (samples generated by a mix of GS and rolling) with C values comprised between 900 and 1,000 microns.
3. In this respect, Zone K is quite similar to the following zones, so inaugurating a possibly new type of functioning. A last feature that will be met further downstream is a wider spectrum of the CM image, in the sense that M values are widely scattered in the different segments (200 to 700 microns in PQ segment; 150 to 250 microns in the upper QR segment;

90 to 200 microns in the lower QR segment). It is true for PQ and QR segments. The explanation of this features may be the existence of proper processes, i.e. a backwater effect, or the inundation of flat vegetated landforms, where the sudden slowing of flow may help trap organic particles and fine particles, which in upstream sites and zones would be transported downstream. Another possible explanation may be a high concentration of sand in the suspension, and these two explanations may coexist.



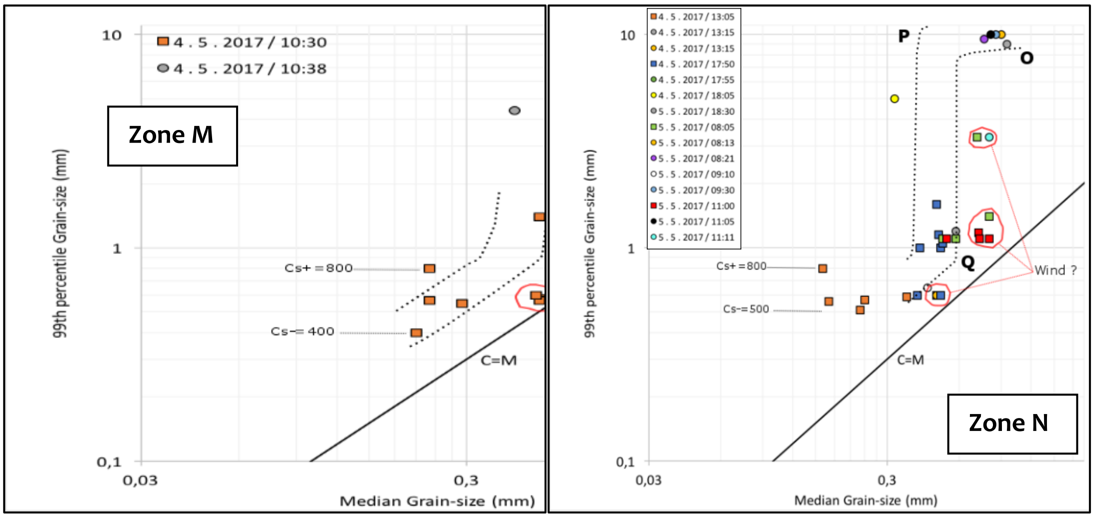
Zone L (figure above) — Zone L is another complex zone, with differences to and similarities with zone K. Turbidity is high even at low flow, probably due to the Chindwin inputs. Although, during the field expedition the Ayeyarwady was more turbid in appearance than the Chindwin, highlighting the variability of the system.

1. Eight of the sites sampled in the channel bed pertain to the PQ segment, as sand from graded suspension more or less enriched in coarser particles, belonging to the class of sand or the class of small gravel. A similarity with zone K is the presence of granules (segment PQ) in two emerging bars (3/5/2017, 8:05 a.m.; 3/5/2017, 17:05 a.m). As noted above, they may be explained by the local conditions in terms of landforms and processes, i.e. the possibility of rolling over upper bars or platforms.
2. Three sandbars were shaped in graded suspension deposits (QR segment) with C values comprised between 600 and 200 microns (2/5/2017, 5:45 a.m.; 3/5/2017, 10:35 a.m.; 4/5/2017, 8:10 a.m. p.m.). These bars have a grain-size similar to the grain-size of channel samples, along with probably the same origin in terms of processes. The first one has poorly sorted sand (low M values explained by the trapping of finer sand?), while the two other ones are slightly coarser and better sorted. An interesting difference with zone K is the very good sorting of a significant number of sand samples (pointing very close to the C = M line). It may be due to the velocity of the flow receding very slowly, allowing the finer particles to be winnowed out of the deposit. This may also be due to wind sorting over the flat bars.

Zone M (figure below)

1. Two in-channel sites were sampled; the sediment belongs to PQ segment.
2. One site was sampled on a bar, with sediment belonging to graded suspension (segment QR), except one sample belonging to segment PQ. C values are comprised between 400

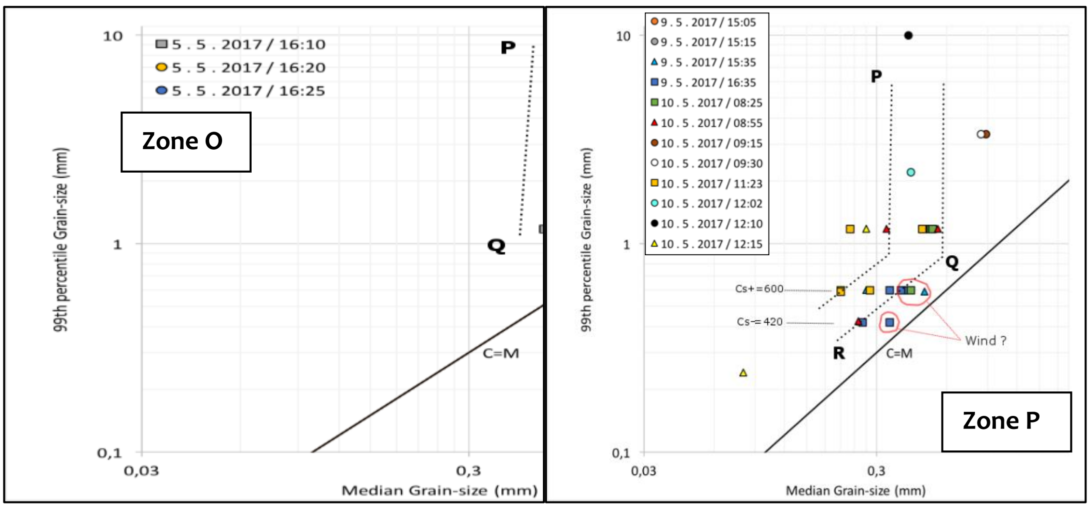
and 800 microns. As in zone K and L, the M value is scattered with both very good and poor sorting (see above for possible explanations including wind action).



Zone N (figure above) — This zone is similar to the complex zones of K and L until a certain point.

1. Nine samples were collected on the channel bottom; most of them are at the upper limit of segment PQ and segment OP (rolling). Grain-size is sand and small gravel.
2. Two sets of samples were shaped by graded suspension and rolling (PQ segment): one set is mixed (GS and S+R), and one set is shaped in graded suspension enriched with fine sand.
3. Four sampling sites were selected on sandbars: side bars (5/5/2017, 1:05 p.m. and 5/5/2017, 8:05 a.m.), a sandy island (5/5/2017, 11:00 a.m.), and a mid-stream bar (4/5/2017, 17:50 p.m.). C values are comprised between 500 and 800 microns.
4. The segments with very well-sorted sediment may be submitted to the influence of the wind (four sandbars).

Zone O (figure below): This zone presents the same pattern as the previous ones, on a few samples, i.e. a bar and channel deposit belonging to the PQ segment, with an important sandy matrix.

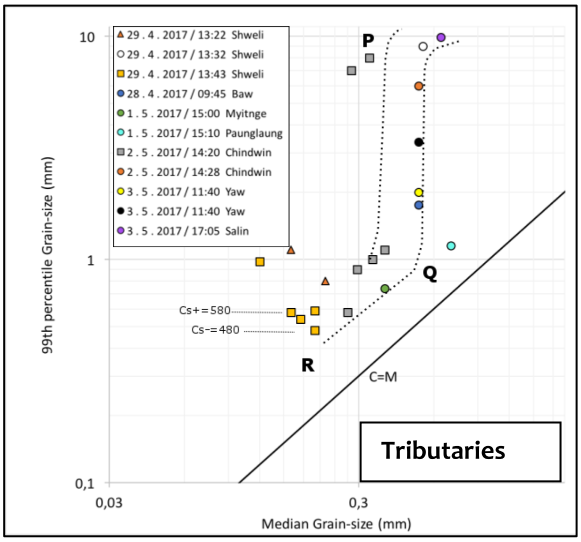


Zone P (figure above)

1. Six samples, taken in the channel, belong to the PQ segment; they are rich in sand, which affects the median (constant value around 400 microns), but two of them are quite well sorted (M at 800 to 900 microns, C at 1,200 microns).
2. Three bars were sampled (10/5/2017, 11:23; 10/5/2017, 8:25 a.m.; 10/5/2017,4:35 p.m.). The C values are comprised between 600 and 420 microns. Two of the sandbars are made of sand both from graded suspension and from S+R, while one of them is made of pure graded suspension. The samples of site 10/5/2017, 11:23 a.m. are poorly sorted, with sediment from graded suspension enriched in finer sand; again, wind may have positively influenced the sorting of sand.
3. Samples from eroded banks display the same features as samples from fresh bars; this zone is similar to zones K, L, M, and N.

Zone Tributaries (figure below)

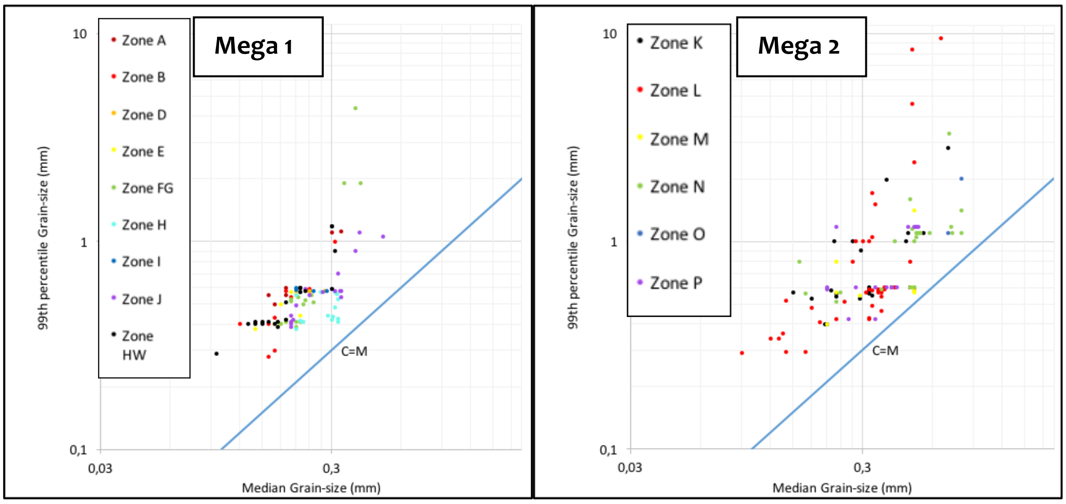
- Shweli — The sandbar is made of well-sorted sand deposited as graded suspension, except for a poorly sorted sample including coarse sand (mix of GS, S+R, and fine sand). The channel sample belongs to PQ segment.
- Baw, Myintnge, Paunlaung, Yaw, and Salin — Samples were collected in the channel; they are mostly composed of medium and coarse sand belonging to GS and S+R.
- Chindwin — The sampled bar displays two facies: a finer facies from graded suspension and the finer part of PQ (S+R), and a coarser facies (limit of PQ and OP = rolling of particles close to 8 to 9 mm).



Grouping zones in mega-zones

The zones selected according to their geomorphology as observed on satellite imagery must be reconsidered in the light of the CM image study. The transport processes, mostly distributed between rolling and graded suspensions, help group the geomorphic zones into two sets of mega-zones:

- **Mega-zone 1** (figure below) — From the headwaters of the Ayeyarwady > zone J = association of sandbars and channel deposits with rolled particles and sand-rich granule deposits. The hypothesis is that these deposits are post-flood peak deposits, which fossilize gravel and eventually cobbles. The deposits are well sorted (parallel to C = M line and close to this line). Some of the sandbars contain some rolled particles, which only occurs in zones A, F, G and J.



- **Mega-zone 2** (figure above) — From zone K to Q, river sediment is deposited by the same kind of processes as in mega-zone 1. However, the differences are significant:
    1. Samples taken in terrestrial landforms are more enriched in rolled particles, which underlines the fact that there exists a kind of continuum at the local scale between bed processes (rolling) and terrestrial landforms (bar platforms and active bars).
    2. Landforms, both aquatic (channel) and terrestrial (platforms and active bars) display sediment spectra characterized by well identified processes (SG, and SG+R with homogeneous well-sorted samples), but the deposits are enriched in sand, probably trapped by landforms, vegetation, and/or conditions facilitating reduction of velocity and then deposition of finer deposits.

  These features, including diverse factors explaining poor sorting, may be strongly influenced by high concentrations in suspended matter, which could reduce the efficiency of sorting processes, producing a type of overloaded river at least in mega-zone 2.

Continuity of the CM image, a describer of functioning at the watershed scale

CM imaging alone is not the best method for assessing with precision the energy at play in the fluvial system. It is simply an indicator, but its gross value is nevertheless interesting.

Continuity of grain-sizes in the CM graph was not considered as a normal feature by Passega. Passega (1964) noticed the 'absence of certain sizes, generally ranging between 500 and 1,000 microns'. This grain-size gap, studied along the Adige River in Italy, 'was attributed to the fact that grains slightly larger than those transported in suspension are the most difficult to roll and are soon abandoned by the current'. Shaw and Kellerhals (1982) proposed another hypothesis. They showed that granules are easily destroyed (crushed, notably) in the processes of transport because they easily roll or are trapped in the upper bed layer, while medium sand, being transported in suspension, escapes this destruction. This is why in large rivers, and in particular in downstream reaches, granules have disappeared from the sediment spectrum, creating a sediment hiatus between sand and gravel.

Considering CM units in the CM graphs of the Ayeyarwady, a hiatus between GS units (segment QR) and segment PQ is likely a reality from the headwaters to zone J. On the contrary, the case is that coarse sand and granules have not disappeared in the lower Ayeyarwady (zones K to Q) since samples point in the CM graph quite continuously between graded suspension and rolling.

A possible hypothesis is that tributaries flowing seasonally from the hilly regions of the dry zone are able to transport these sediment fractions to the main trunk of the fluvial system. These lower zones would then receive high concentrations of fines and the complete spectrum of fines.

Graded suspension values, an indirect describer of energy

Passega proposed that low and high values of C could help in discriminating between deposits from graded suspensions. QS^+ and Qs^- expressed in microns provide quantitative assessment of maximum and minimum energy displayed in the deposition process, at least in the sampled sites. The upstream-downstream change of Cs values in each zone is presented in the Table below.

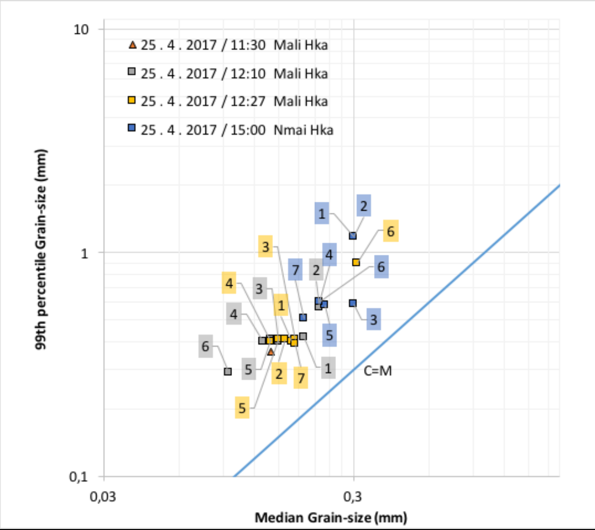
Maximum and minimum C values by zone

	HW	A	B	D	E	G	H	I	J	K	L	M	N	O	P
Cs^+	600	600	600	480	470	450	480	580	700	600	600	800	800	600	600
Cs^-	300	480	280	320	380	380	280	560	380	400	200	400	500	420	500

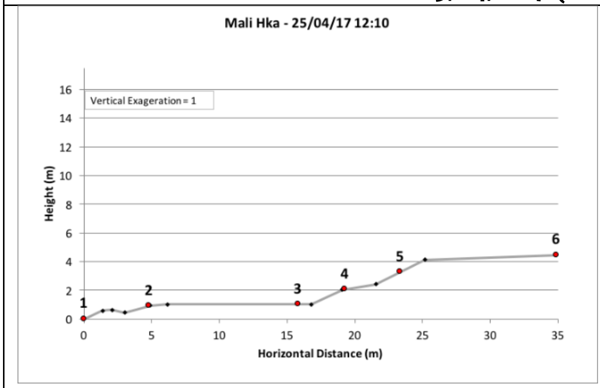
– Cs^+ values are indicators of maximum energy displayed in the turbulence: they stand up to 600 microns in zones HW-A-B, and are lowered to 450 to 480 microns in zones E-G-H. Values increase in I (580 microns) and again in zone J (700), K-L-M (600), N (800), and Q (600).

– Cs^- values are indicators of the minimum energy displayed in the turbulence of this river. They are more variable, with values comprised between 200 and 560 microns along the river continuum; more generally they exceed 280 microns.

Zone Headwaters



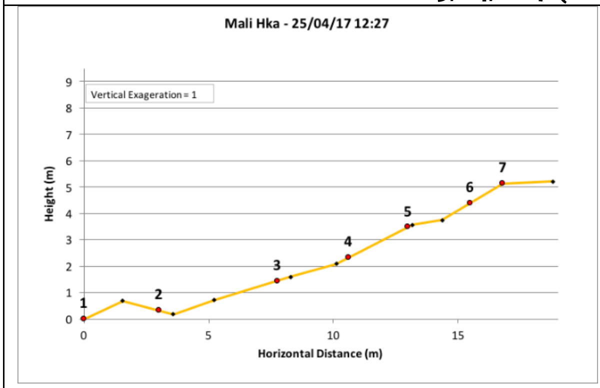
25/04/2017 (12 :10) Recent bank



	M	C
1	190	420
2	220	570
3	150	400
4	130	400
5	140	410
6	95	290

The alluvial deposits lay on the bedrock and channel mobility is non-existent. Small secondary channels are shaped inside the deposits and watered during the floods.

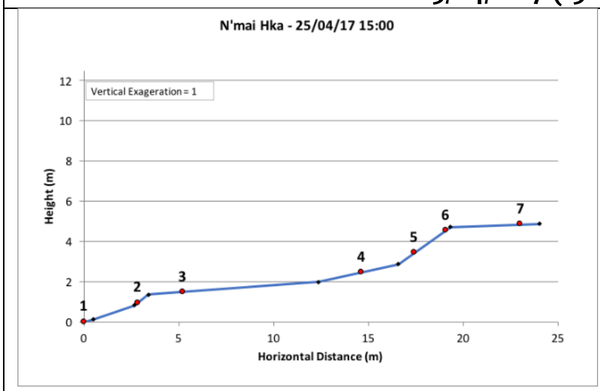
25/04/2017 (12:27) Recent bank



	M	C
1	170	400
2	160	410
3	175	410
4	140	400
5	150	410
6	310	900
7	175	390

The alluvial deposits lay on the bedrock and channel mobility is non-existent. Small secondary channels are shaped the deposits and watered during the floods.

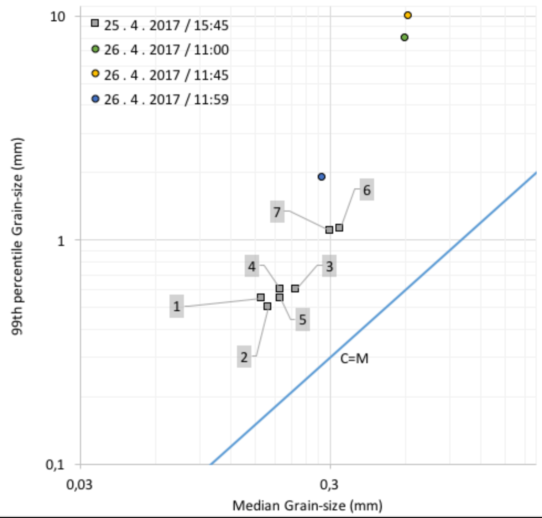
25/04/2017 (15 :00) Recent bank



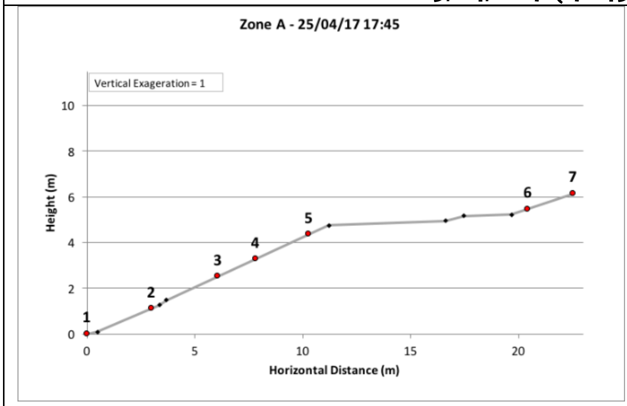
	M	C
1	300	1180
2	300	1180
3	300	590
4	220	600
5	230	580
6	220	600
7	190	510

	
Alluvial deposits on bedrock inside a confined reach with swift current.	
	
Mali Hka: Reworking of ancient gravel deposits due to gold mining. The reddish colour of the gravel and their matrix contrasts with the gray colour of recent sand deposited by floods in protected areas.	N'mai Hka: A sandbar accreting to downstream. The core of the bar is made of fresh gravel transported by present floods. The top of the bar is made of gray medium size sand.

Zone A



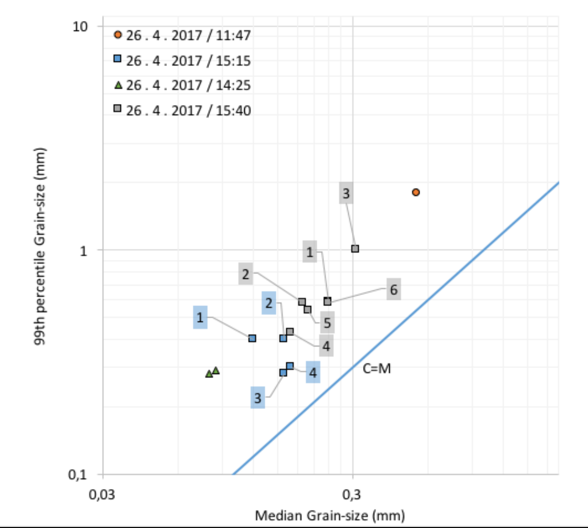
25/04/2017 (17 :45) Recent bank



	M	C
1	160	550
2	170	500
3	220	600
4	190	600
5	190	550
6	330	1,120
7	300	1,100

The deposits lay on bedrock in a confined reach. The bedload of this reach is composed of large cobbles stained by iron oxides and trapped on the uneven surface of the bedrock forming the islands and banks. The photo shows some of them and a gravel bar. Sand is deposited over gravel in sheltered areas, downstream of rocky and vegetated area.

Zone B

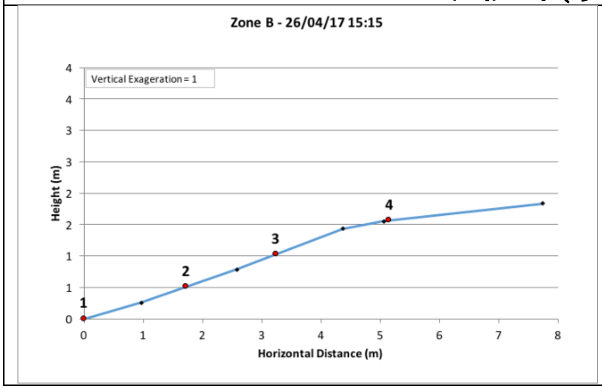


26/04/2017 (14 :25) Old bank

	M	C	Location
1	85	290	1.2 m above water level
2	80	280	2.6 m above water level

Alluvial deposit eroded by a flood and partly revegetated.

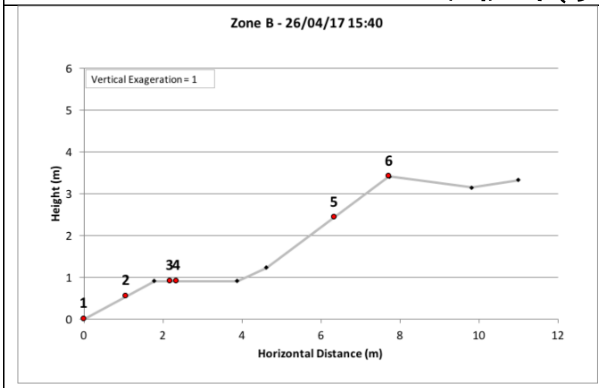
26/04/2017 (15:15) Recent bank



	M	C
1	120	400
2	160	400
3	160	280
4	170	300

Stable bank, no lateral shifting since 1988.

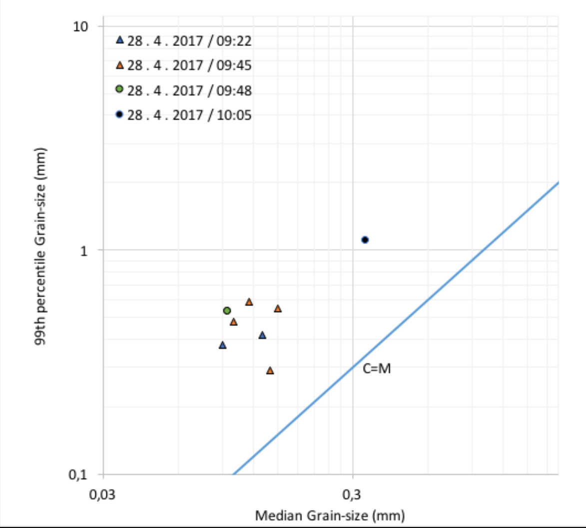
26/04/2017 (15:40) Recent bank



	M	C
1	240	590
2	190	580
3	310	1,000
4	170	430
5	200	540
6	240	580

Sampling a transect on a sandbar from the water level to the top of the bar (left). The bar is in a secondary channel that is active during the flood season. Flow turbulence transports sand in the water body during the flood and sand deposition occurs when velocity and turbulence decrease. Part of the vegetation develops after the sand is deposited. The channel has been stable since 1988.

Zone C



28/04/2017 (09:22) Old bank

	M	C	Location
1	90	380	1 m above water level
2	130	420	2.1 m above water level

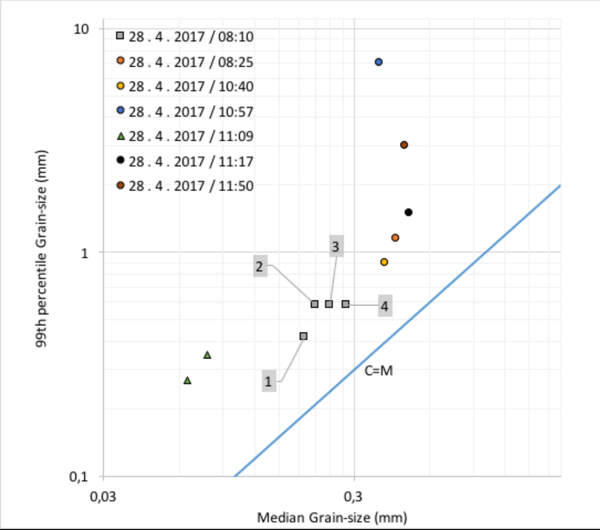
Left old bank deposit showing active erosion and supporting multi-year vegetation. The bank is composed predominantly of fine sand. It is located at the downstream end of zone C, at the end of the single bedrock controlled channel. Sampled at the water level and 1 m above the water level.

28/04/2017 (09:45) Old bank

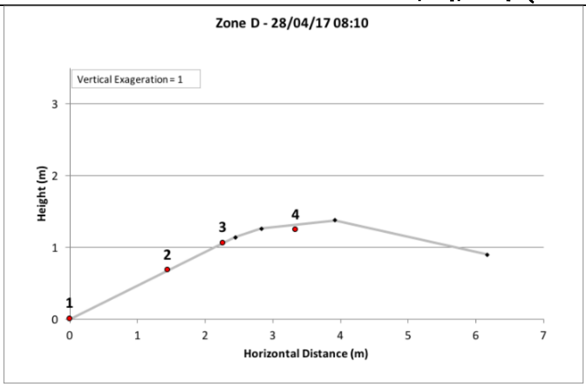
	M	C	Location
1	100	480	water level
2	150	550	1 m above water level
3	140	290	2 m above water level
4	115	590	3 m above water level

Samples: Right bank deposit, sampled at water level, +1, +2, +3 m. Eroded old bank on a vegetated island. This bank is 4 to 5 m high and composed of consolidated silty sand. Woody flood debris is visible on top of the bank. Despite its elevation, this deposit may be considered as relatively recent as it is in the transition area from the single channel Zone C to the highly braided Zone D.

Zone D



28/04/2017 (08:10) Recent bank



	M	C
1	190	420
2	210	580
3	240	580
4	280	580

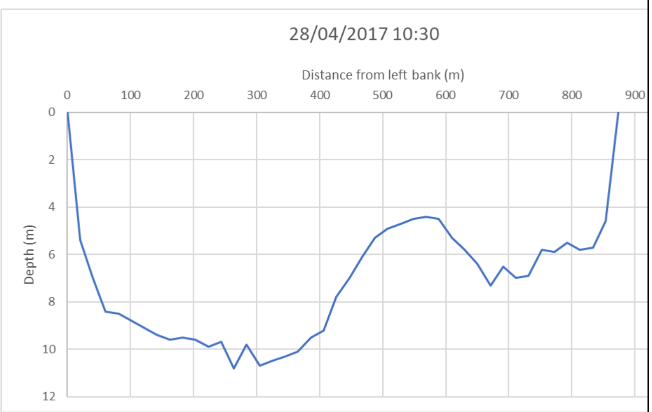
The deposition/exposure of this bar began after 2007; its banks have slowly eroded. The bank displays a vertical section related to lateral erosion with cohesive dark layers, and a cover of fresh sand which was sampled.

28/04/2017 (11:09) Old bank

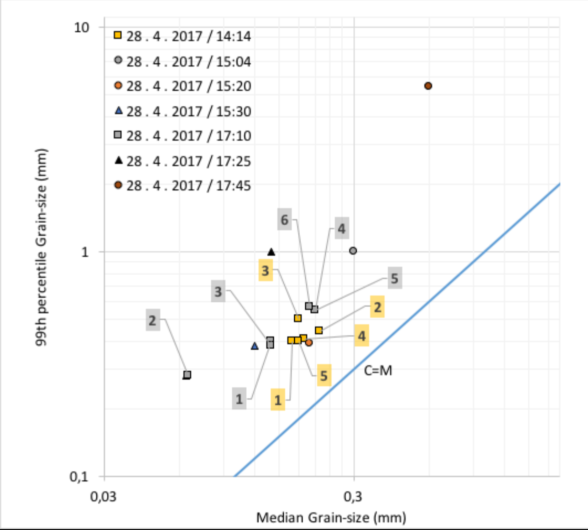
	M	C	Location
1	65	270	water level
2	78	350	1 m above water level

A 2 m high bank eroded by the lateral shifting of a channel. The deposits alternate between light sand-rich layers and darker silty-sand layers. Lateral erosion occurs readily in this non-cohesive sediment. This bank was deposited before 1988 and the lateral erosion is active.

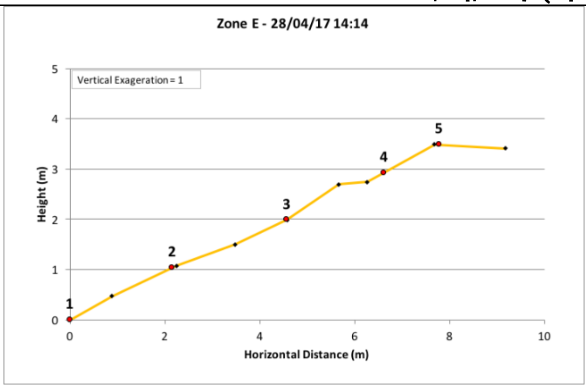
Channel cross-sections – Zone H (facing downstream)



Zone E



28/04/2017 (14:14) Recent bank



	C	M
1	170	400
2	220	440
4	180	500
5	190	410
6	180	400

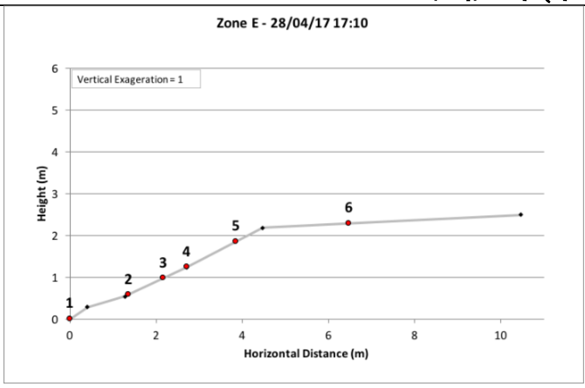
These deposits are located along stable river margins.

28/04/2017 (15:30) Old bank

	M	C	Location
1	120	380	1 m above water level
2	64	280	2 m above water level

Right old bank deposit located in narrow (~600 m) singe channel section. The bank is approximately 4 m high and composed predominantly of fine sand and silt. The bank toe has a sandy inset that may likely be younger.

28/04/2017 (17:10) Recent bank



	C	M
1	140	400
2	65	280
4	140	380
5	210	550
6	210	550
7	200	570

Photo of a recent bar made of fresh sand deposited by the 2016 flood. This lateral bar is located adjacent to ancient stable banks downstream of a gorge. The CM image is based on samples from this bar.

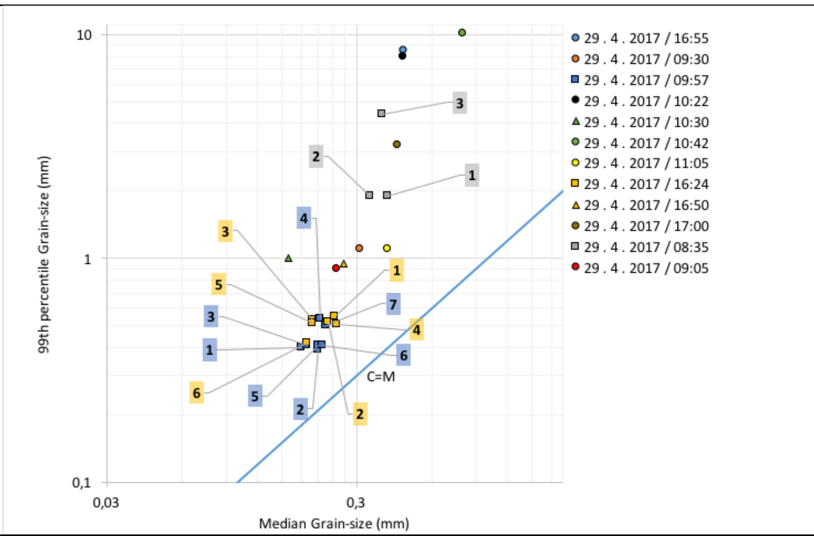
28/04/2017 (17:25) Old bank

	M	C	Location
1	140	1,000	2.5 m above water level

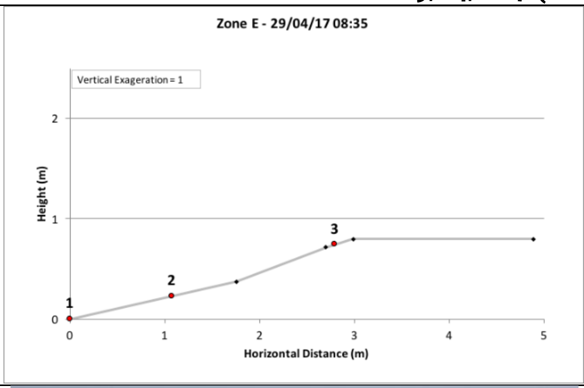
Right old bank deposit, located about 6 km upstream of Shwegu. Basal unit contains well rounded cobbles; upper unit is more massive and poorly sorted, containing over 20% each silt/clay, fine and medium sands, and ~10% gravels.

Channel cross-sections – Zone H (facing downstream)

Zone F-G



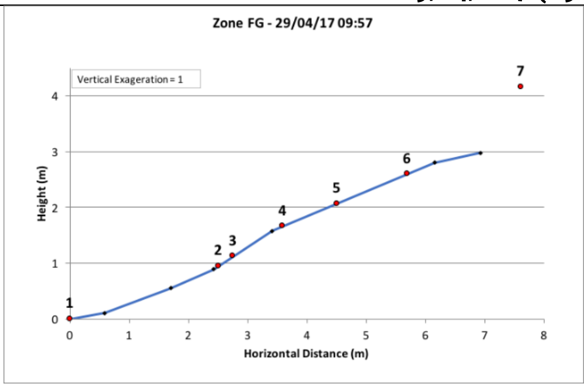
29/04/2017 (08:35) Recent bank



	C	M
1	400	1,900
2	340	1,900
4	380	4,400

Sandbar built up by the 2016 flood. Construction of the bar began after 2012 but the balance between erosion/deposition is in equilibrium. The sampling transect runs across the bar.

29/04/2017 (09:57) Recent bank



	M	C
1	180	400
2	210	390
3	190	410
4	215	540
5	210	410
6	220	410
7	225	500

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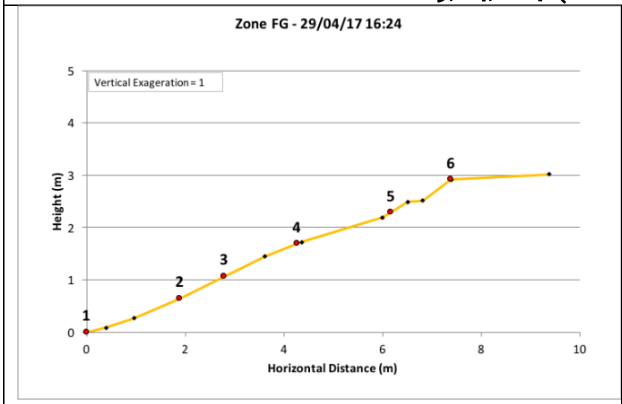
This young deposit is dated post-2006 but lateral erosion is active and this landform is reducing in size.

29/04/2017 (10:30) Old bank

	M	C	Location
1	160	1,000	Mid

Older alluvium, pleistocene based on the geologic map.

29/04/2017 (16:24) Recent bank



	M	C
1	245	550
2	230	520
3	200	530
4	250	510
5	200	515
6	190	420

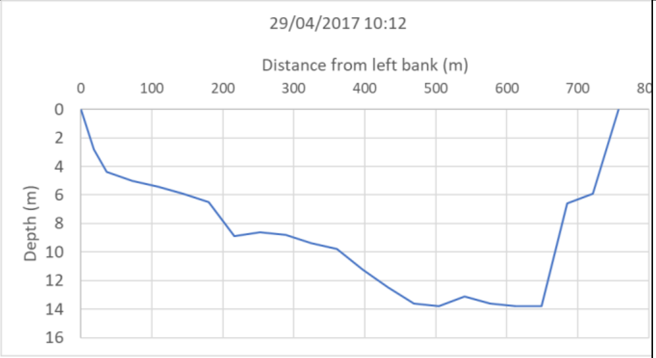
This deposit has been building up since 2000. The sampled bank is actively eroded.

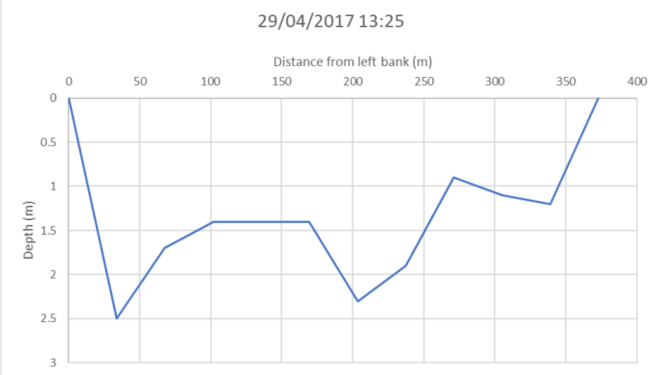
29/04/2017 (16:50) Old bank

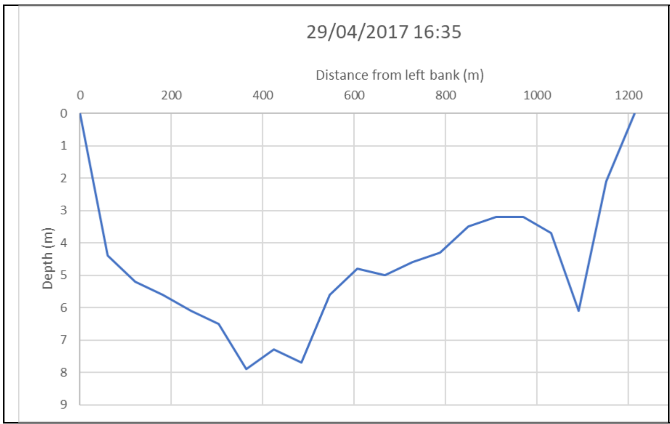
	M	C	Location
1	265	950	1 m above water level

Left bank old deposit that pre-dates 1988 and is experiencing lateral erosion. The bank contains fine and medium sand with minor amounts of gravel. The floodplain is developed for agriculture.

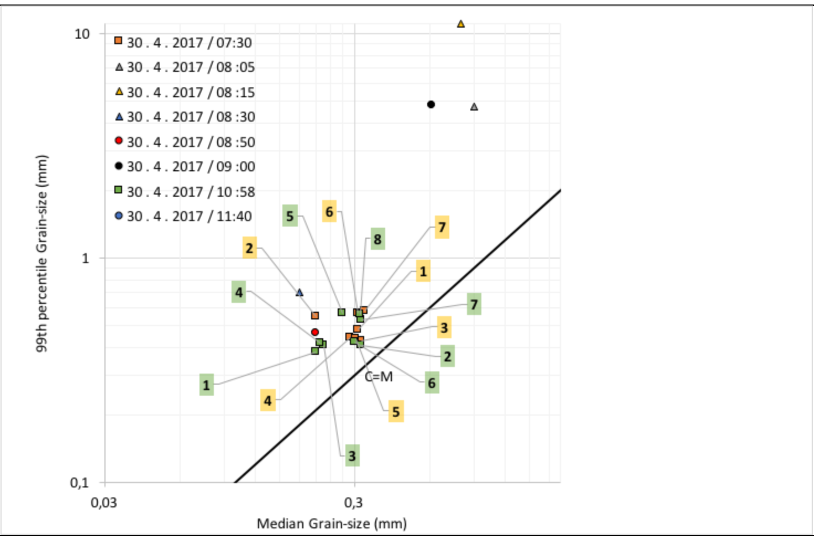
Channel cross-sections – Zone F-G (facing downstream)



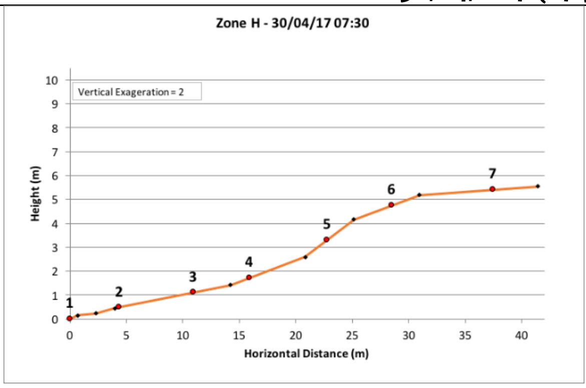




Zone H



30/04/2017 (07:30) Recent bank



	M	C
1	310	480
2	210	550
3	320	425
4	290	440
5	305	435
6	310	570
7	330	580

Left bank lateral deposit in a confined reach, which may be post-2013. Sampling transect at the downstream end of a sandbar mostly built up in 2016 and colonized by grass. Wind has shaped sand ridges.

30/04/2017 (08:05) Old bank

	M	C	Location
1	900	4,700	?
2	800	11,000	?

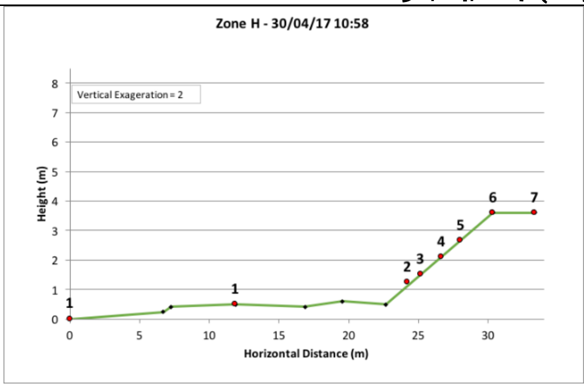
Left old bank adjacent to active bank sampled at 07:30 in Sagaing shear zone. The bank is approximately 5 m in height, indurated and weathered, and shown as Holocene on the geologic map. Both samples are composed of medium and coarse sand.

30/04/2017 (08:15) Old bank

	M	C	Location
1	180	700	2 m above water level

Right bank sample collected opposite previous old bank sample. Sample collected at approximately 2 m above water level at break in slope. The floodplain is cleared and developed for agriculture. The bank is finer-grained as compared to opposite bank, containing about 50% each of fine and medium sand.

30/04/2017 (10:58) Recent bank

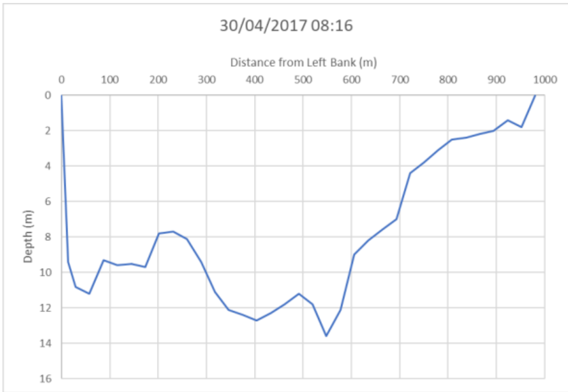


	M	C
1	210	380
2	320	410
3	225	410
4	220	415
5	270	570
6	300	420
7	320	530
8	315	560

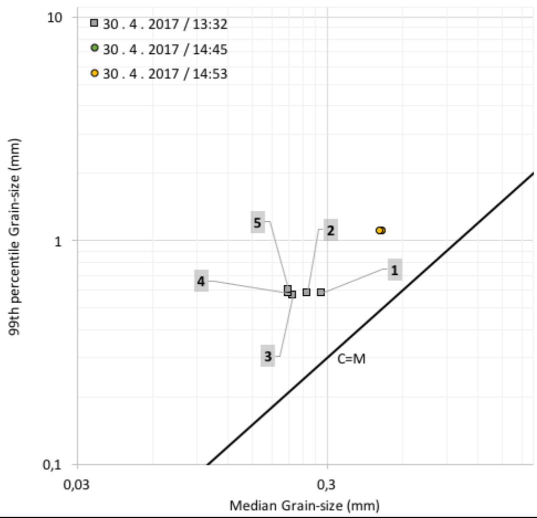
Landform shaped by deposition and erosion since 1988. The top of the landform has not been covered by water during the dry season since 2008, based on satellite imagery.

A bank eroding to the detriment of a large sandbar. Depositional features are visible and include: wet, silty sand deposited by a slower current, and lee faces of accreting deposits.

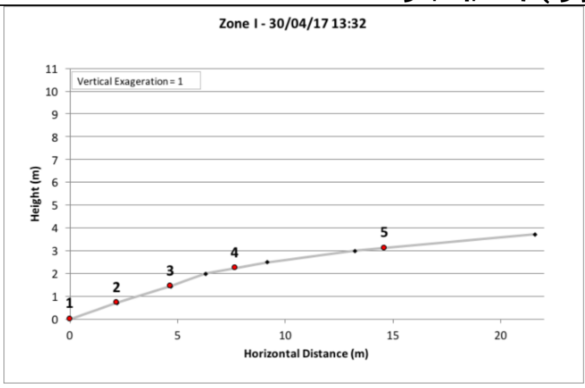
Channel cross-sections – Zone H (facing downstream)



Zone I



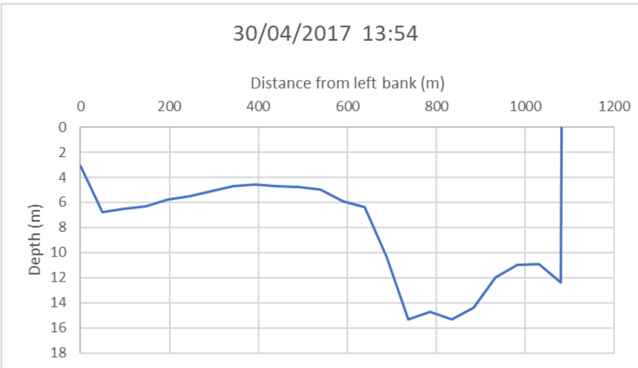
30/04/2017 (13:32) Recent bank



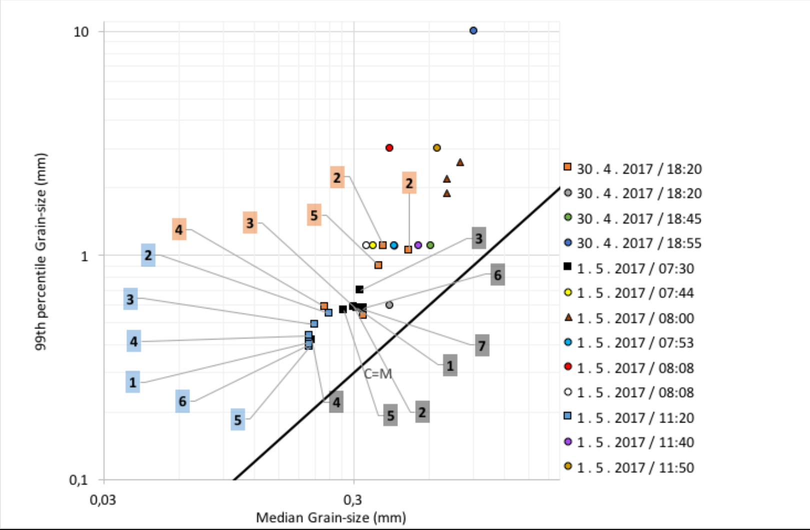
	M	C
1	285	580
2	250	580
3	220	570
4	210	585
5	210	600

This recent lateral deposit is located in a confined reach. Built up by the 2016 flood, it is colonized by vegetation. It is protected from upstream flow by a promontory belonging to ancient formations. Note the swale behind the bar, with denser vegetation on finer sediment. This sandbar was sampled for the CM image study.

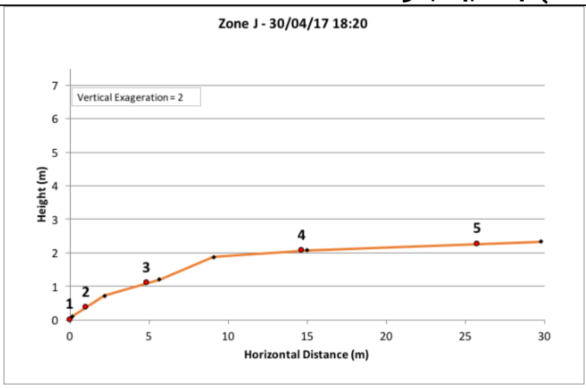
Channel cross-sections – Zone I



Zone J



30/04/2017 (18:20) Recent bank

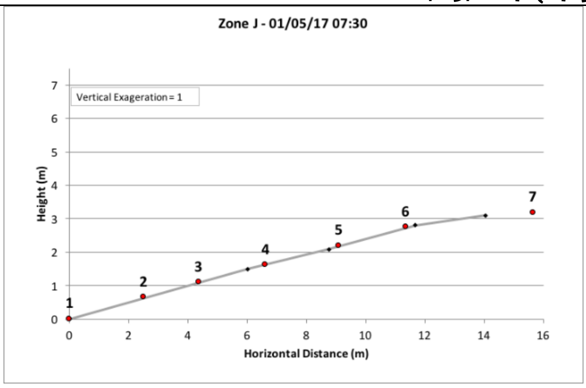


	M	C
1	500	1,050
2	395	1,100
3	330	540
4	230	590
5	380	900

The older part of the deposit (on the right) was deposited before 1988. The fresh deposit is attributable to the last flood and covers the older landform.

7.2.9 The bank is actively eroding. The CM transect was collected across the fresh sand where the tape measure if visible.

01/05/2017 (07:30) Recent bank



	M	C
1	310	580
2	300	590
3	320	700
4	205	420
5	275	570
6	330	580
7	325	575

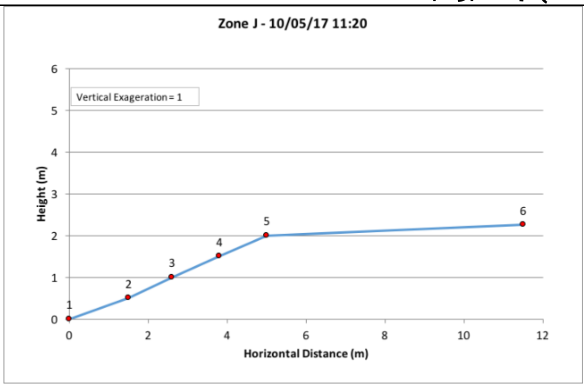
Recent deposition on an ancient landform

01/05/2017 (08:00) Old bank

	M	C	Location
1	710	2,200	Top
2	710	1,900	Mid
3	800	2,600	Bottom

Right older bank behind CM site with recent deposition. The bank shows banded units and cross-bedding with abundant burrows, and is actively eroding.

01/05/2017 (11:20) Recent bank

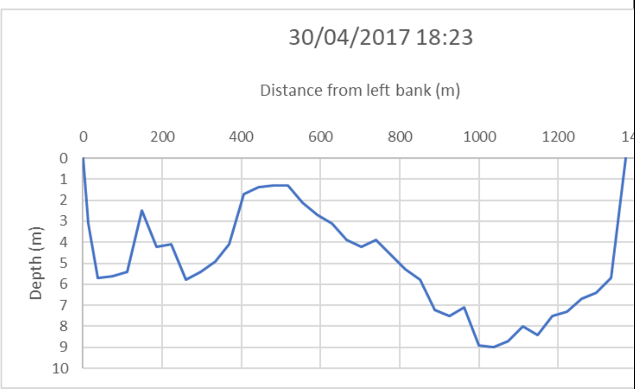


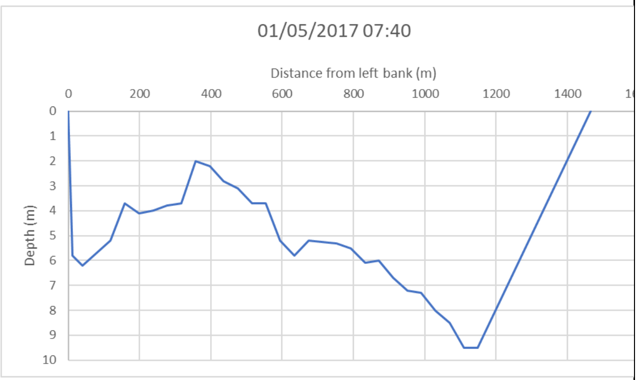
	M	C
1	200	410
2	240	550
3	210	490
4	200	440
5	200	390
6	200	400

Sandbar situated at the bottom of an island; the bar has been built up since 1998. Fresh sand was laid during the 2016 flood by deposition of graded suspension. The bank is currently slowly eroding.

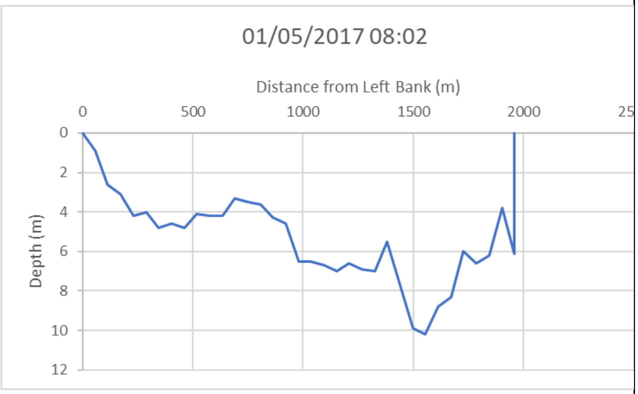
Island landscape of the Ayeyarwady River. Flat bars or alluvial platforms at different elevations, according to their age and possibility of vertical aggradation.

Channel cross-sections – Zone J (facing downstream)

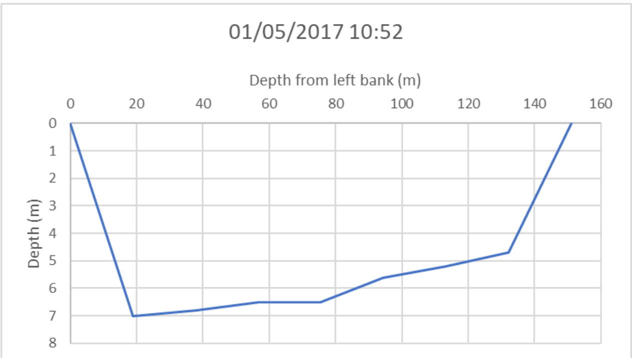



01/05/2017 07:40
Distance from left bank (m)
0 200 400 600 800 1000 1200 1400
Depth (m)
0 1 2 3 4 5 6 7 8 9 10


End of Recorded Depths

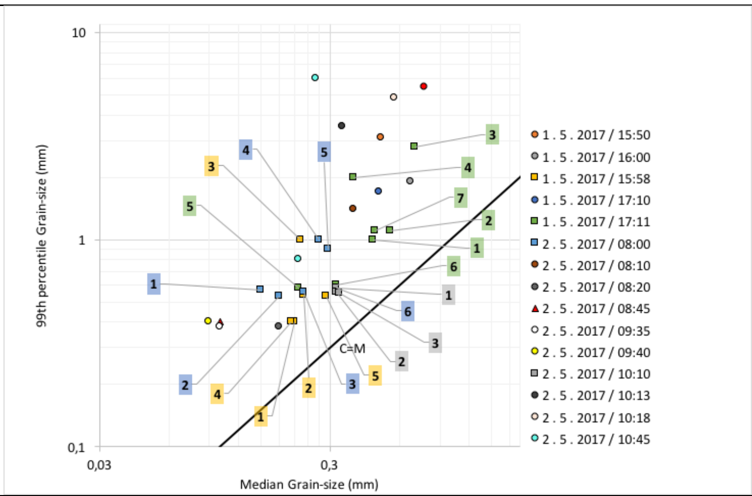

01/05/2017 08:02
Distance from Left Bank (m)
0 500 1000 1500 2000
Depth (m)
0 2 4 6 8 10 12


Min Kun

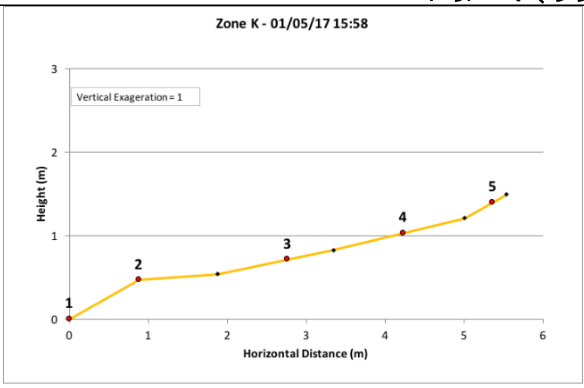

01/05/2017 10:52
Depth from left bank (m)
0 20 40 60 80 100 120 140 160
Depth (m)
0 1 2 3 4 5 6 7 8


Ye Lun Kyaw

Zone K


99th percentile Grain-size (mm)
10
1
0,1
0,03
0,3
Median Grain-size (mm)
C=M
1 . 5 . 2017 / 15:50
1 . 5 . 2017 / 16:00
1 . 5 . 2017 / 15:58
1 . 5 . 2017 / 17:10
1 . 5 . 2017 / 17:11
2 . 5 . 2017 / 08:00
2 . 5 . 2017 / 08:10
2 . 5 . 2017 / 08:20
2 . 5 . 2017 / 08:45
2 . 5 . 2017 / 09:35
2 . 5 . 2017 / 09:40
2 . 5 . 2017 / 10:10
2 . 5 . 2017 / 10:13
2 . 5 . 2017 / 10:18
2 . 5 . 2017 / 10:45

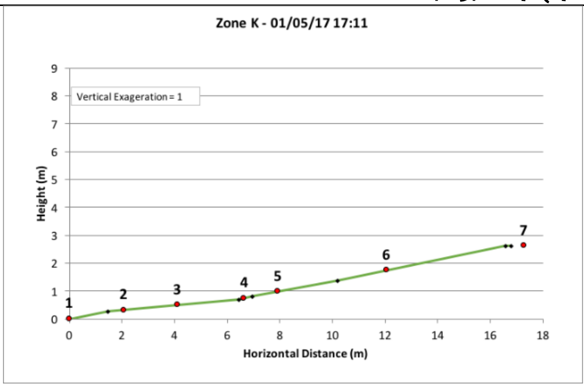
01/05/2017 (15:58) Recent bank



	M	C
1	210	400
2	230	540
3	225	1,000
4	205	400
5	290	530

Right bank sandbank that has existed since 1991, and supports woody vegetation. Now the bank is experiencing lateral erosion.

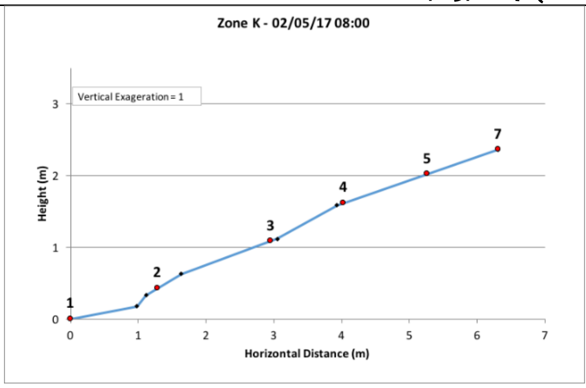
01/05/2017 (17:11) Recent bank



	M	C
1	460	1,000
2	550	1,100
3	700	2,800
4	380	1,990
5	220	580
6	320	600
7	470	1,100

Right bank active bar that has been deposited since 2002. Erosion is presently active along the island margins.

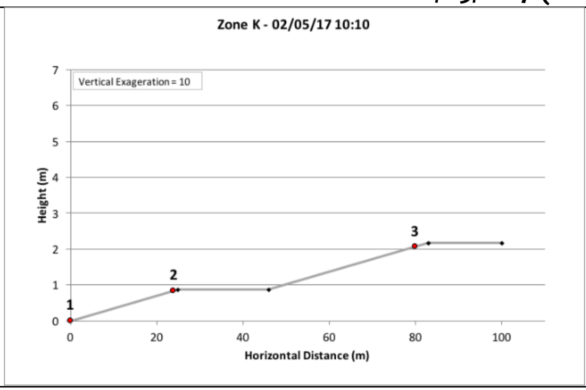
02/05/2017 (08:00) Recent bank



	M	C
1	150	570
2	180	530
3	230	560
4	270	1,000
5	295	900
6	320	580

Left bank lateral bar that has existed since at least 1988, and is now undergoing slow lateral erosion.

02/05/2017 (10:10) Recent bank



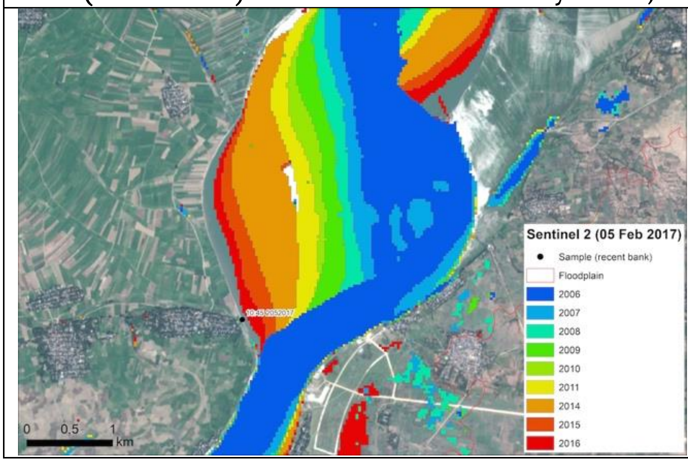
	M	C
1	320	580
2	320	560
3	330	550

Mid-stream bar with low elevation above water level and rapid aggradation, built up after 2011. The cross-section runs across it. Note the importance of dead wood on the bar for promoting deposition. Water marks on the bar relate to flood recession levels.

02/05/2017 (10:45) Old bank

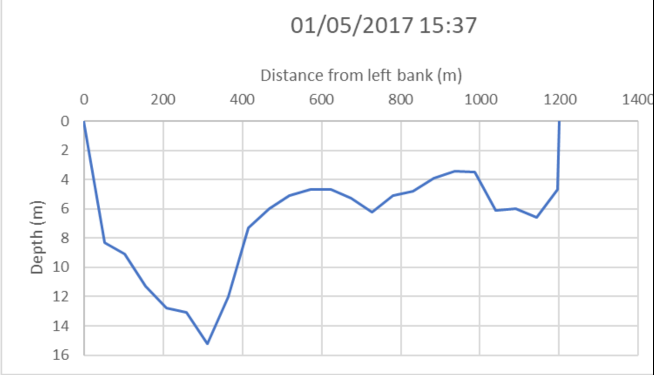
	M	C	Location
1	220	800	Uper fine layer
2	260	6000	Lower material

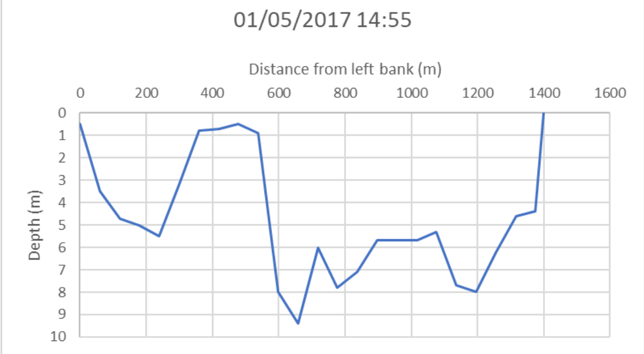
This right bank bar pre-dates 1988 and displays layers of non-cohesive sand (white) topped by silty sand (dark colour). Erosion of this bar is very active, recorded at about 100 m per year.

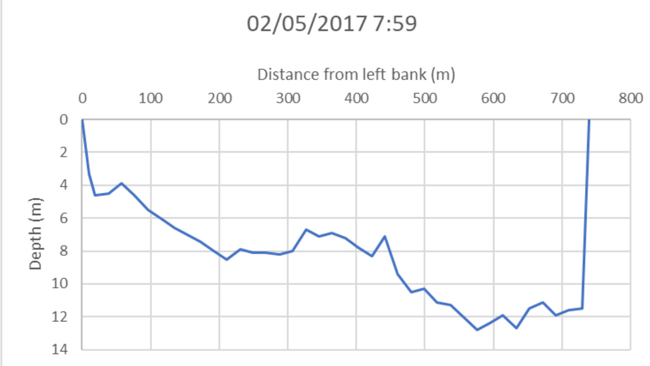


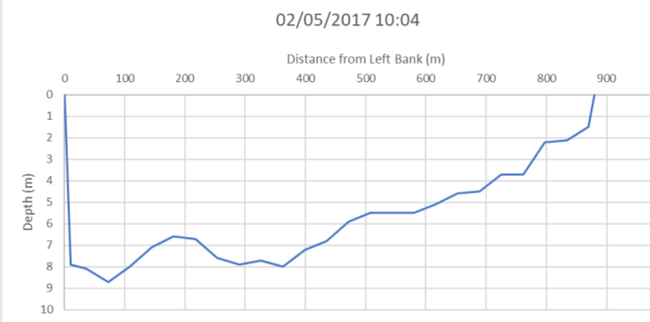
Satellite image analysis showing channel migration and erosion of lateral bar. Rates are of the order of 100 m per year.

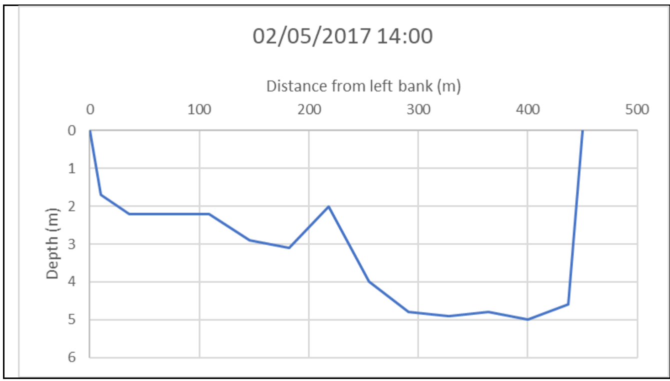
Channel cross-sections – Zone K (facing downstream)



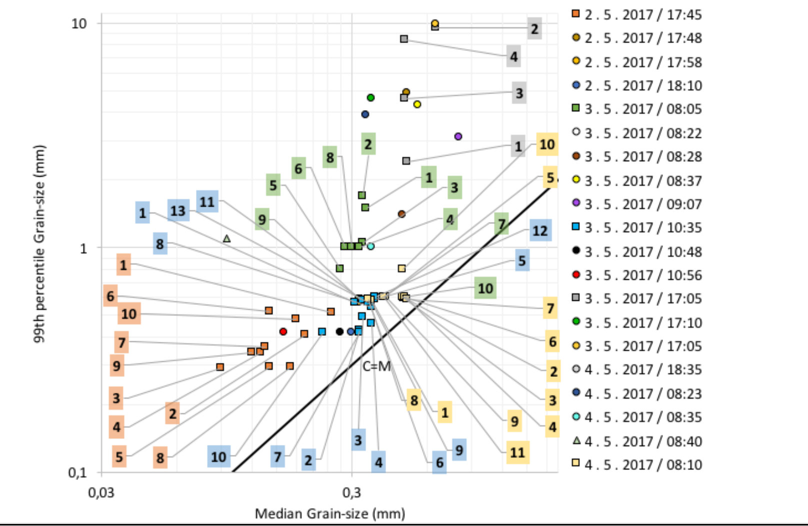




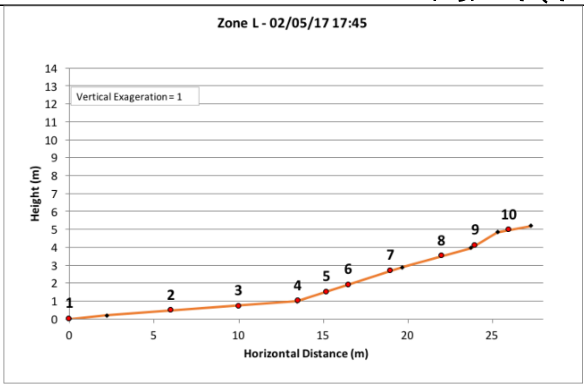




Zone L



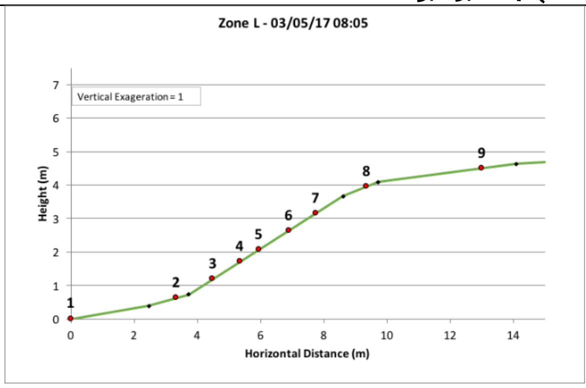
02/05/2017 (17:45) Recent bank



	M	C		M	C
1	250	510	6	140	520
2	195	410	7	135	360
3	90	290	8	170	295
4	130	340	9	120	340
5	140	295	10	180	480

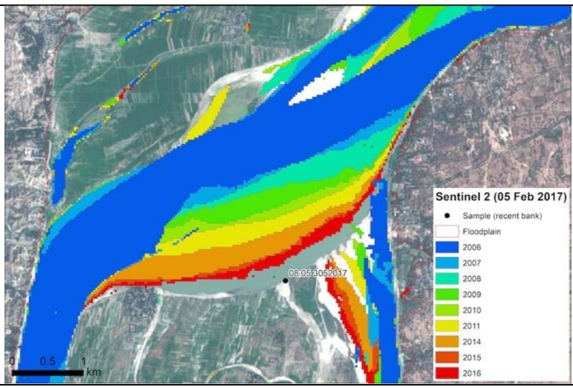
Left bank composed of a recent/active deposit on the lower bank. The upper bank has not been inundated since 1990.

03/05/2017 (08:05) Recent bank



	M	C		M	C
1	340	1,500	6	280	1,000
2	330	1,700	7	400	600
3	330	1,050	8	300	1,000
4	320	1,000	9	320	590
5	270	800	10	480	600

Mid-stream island that has been deposited since 2002. It is presently actively eroding, with the direction of the channel movements shown below.



Channel migration by year. This location is near a recently eroded pagoda and is discussed in more detail in Section 0.

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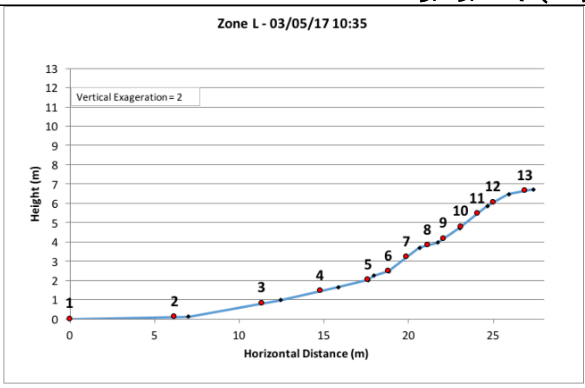
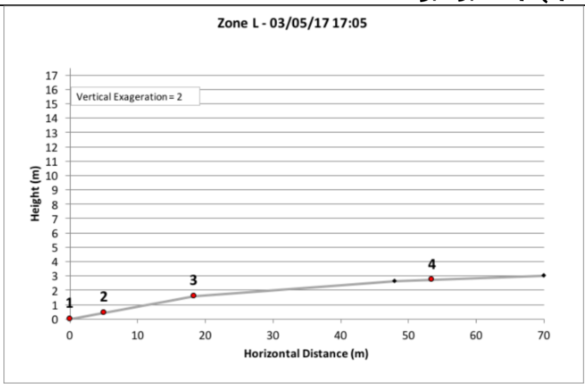
03/05/2017 (10:35) Recent bank



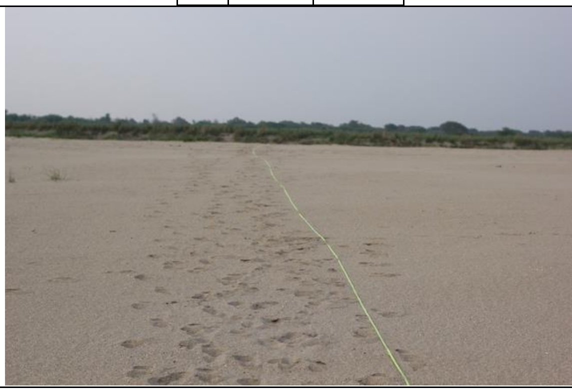
	M	C		M	C
1	310	570	8	360	540
2	320	425	9	360	570
3	330	490	10	230	420
4	360	460	11	330	580
5	370	590	12	370	600
6	350	580	13	350	570
7	320	420			

Right bank deposited since 2008.

03/05/2017 (17:05) Recent bank

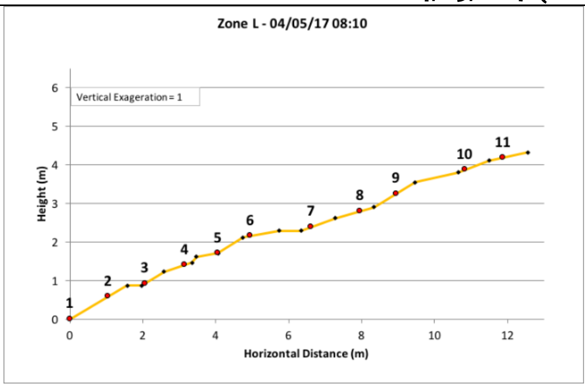


	M	C
1	500	2,400
2	650	9,500
3	490	4,600
4	490	8,400



Extensive low-lying bar deposited post-2007. A very long transect was required to sample this bank.

04/05/2017 (08:10) Recent bank



	M	C		M	C
1	360	580	7	500	590
2	480	600	8	350	590
3	480	600	9	410	600
4	490	600	10	480	800
5	400	600	11	400	600
6	490	600			

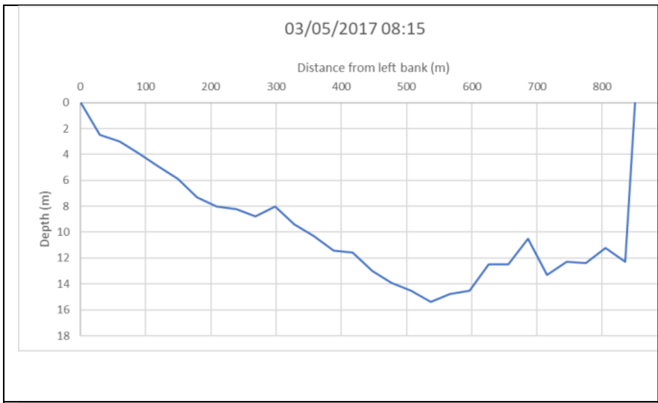
Right bank that has been deposited since 2010. The present elevation shows how much material has been deposited.

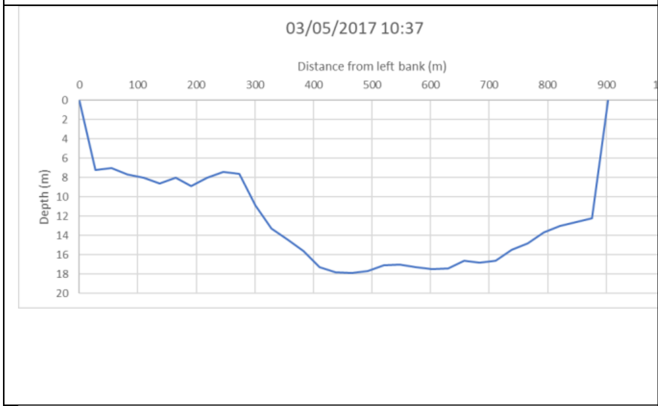
04/05/2017 (08:40) Old bank

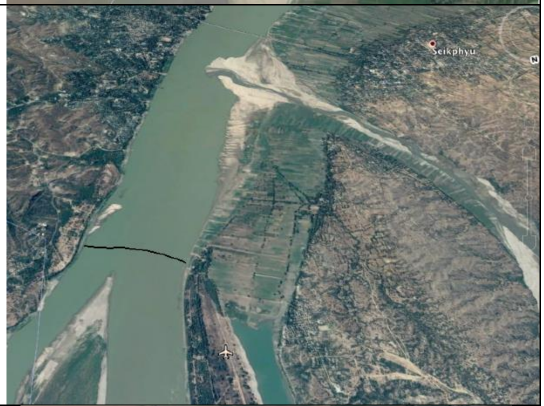
	M	C	Location
1	95	1,100	Fine-grained units
2	480	600	Coarse-grained units

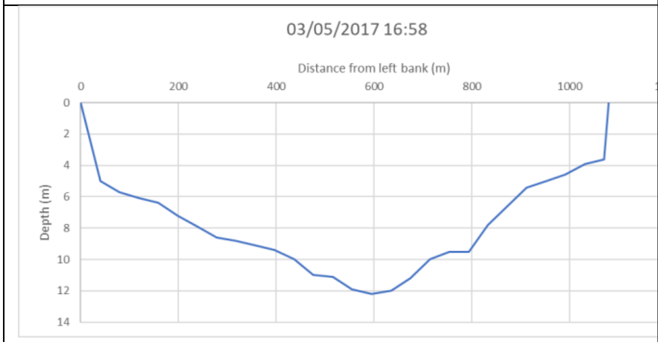
Right bank 2.5 m high unstable bar, consisting of a coarse sand unit overlain by a siltier unit. The bar collapsed during sampling.

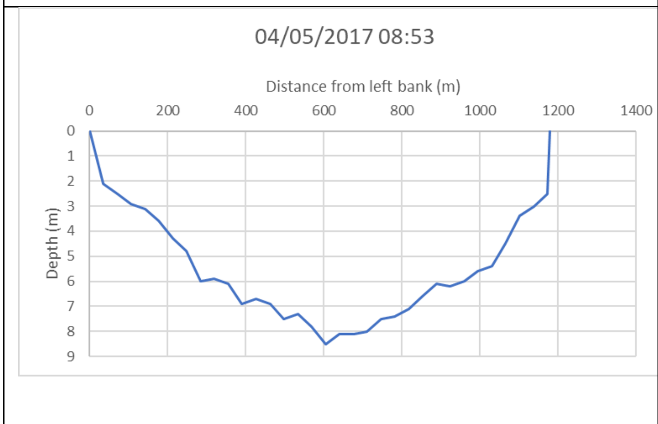
Channel cross-sections – Zone L (facing downstream)



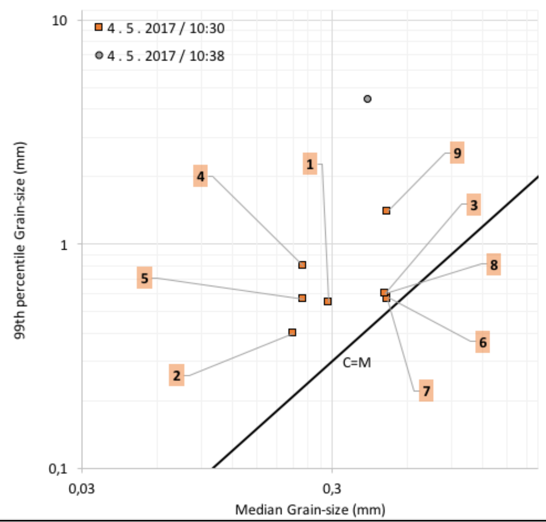




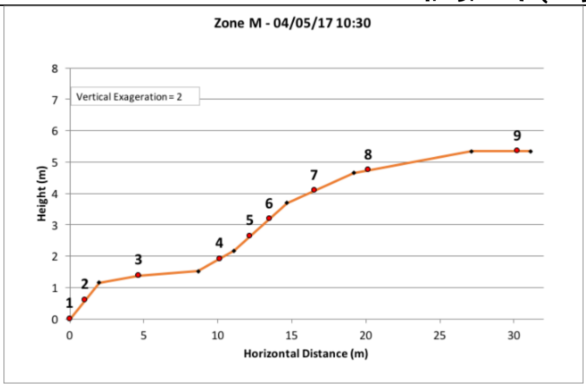




Zone M



04/05/2017 (10:30) Recent bank

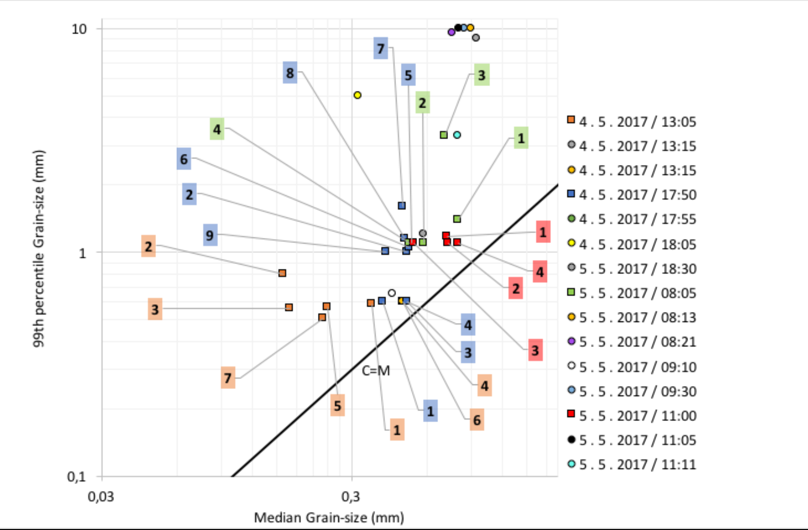


	M	C		M	C
1	290	550	**6**	500	580
2	210	400	**7**	500	570
3	490	600	**8**	490	600
4	230	800	**9**	500	1,400
5	230	570			

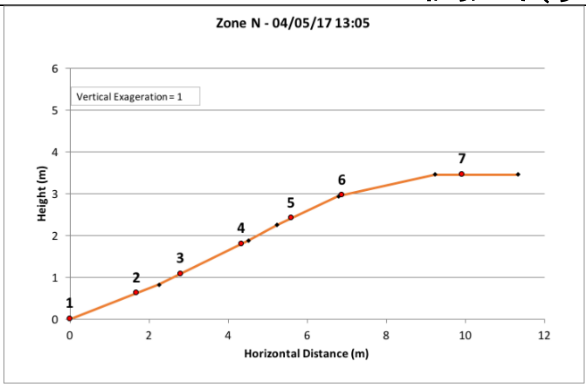
Right bank, large sandbar that has been aggrading since 2010. The foreground is bare, but the remote areas are higher and vegetated, promoting the trapping of sand and finer particles.

Channel cross-sections – Zone M (facing downstream)

Zone N



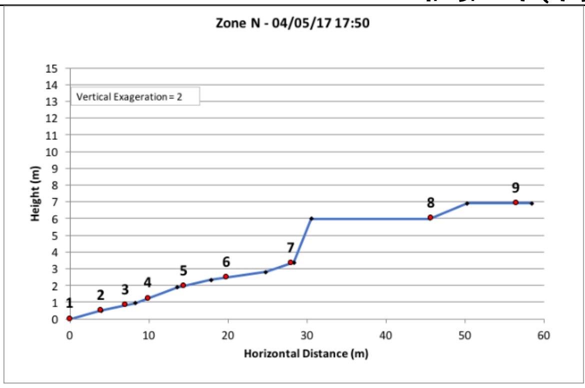
04/05/2017 (13:05) Recent bank



	M	C
1	360	590
2	160	800
3	170	560
4	480	600
5	240	570
6	480	600
7	230	510

Right bank sandbar deposited since 1998 that is actively eroding.

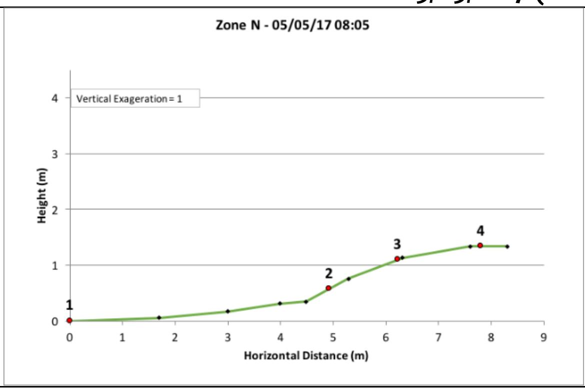
04/05/2017 (17:50) Recent bank



	M	C		M	C
1	400	600	6	510	1,050
2	500	1,000	7	480	1,600
3	500	600	8	490	1,150
4	500	600	9	410	1,000
5	520	1,100			

Left bank on a mid-stream bar that is stable, showing no lateral changes over the past few years.

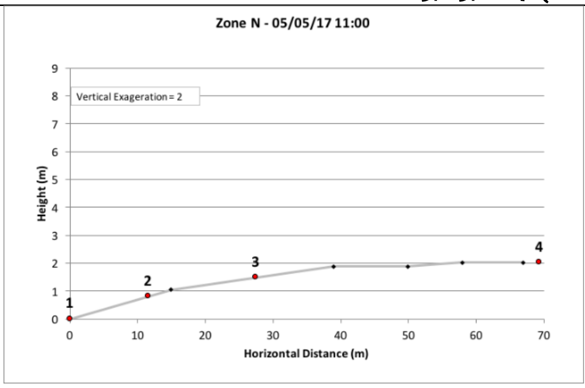
05/05/2017 (08:05) Recent bank



	M	C
1	800	1,400
2	580	1,100
3	710	3,300
4	510	1,100

Right bank bar that contains an abundance of medium sand. The morphology has formed since 2006.

05/05/2017 (11:00) Recent bank

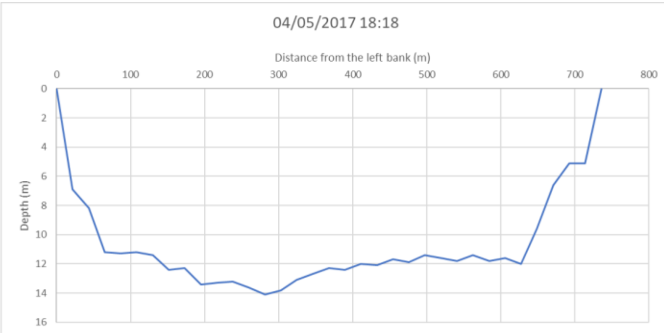


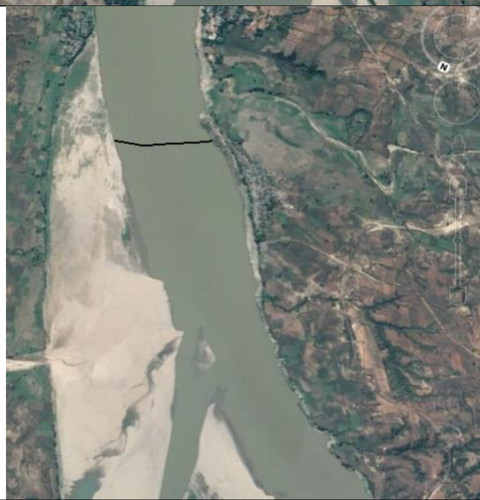
	M	C
1	720	1,180
2	730	1,100
3	530	1,100
4	800	1,100

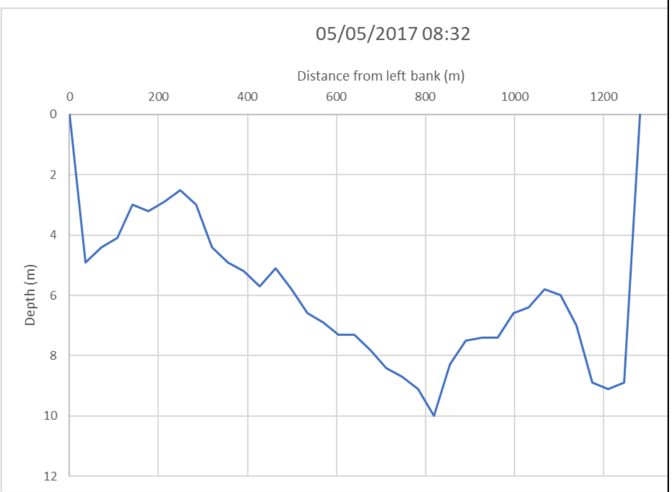
Left bank of mid-stream bar with a flat platform built up after 1996 and presently eroding at the upstream end. Prominent cross-bedding is visible.

Detail of the cross-bedding. These structures occur due to deposition from a flowing river on a sloping surface. The lack of cohesion is responsible for the fragility of the bar. It is topped by a flat layer and affected by wind erosion.

Channel cross-sections – Zone N (facing downstream)







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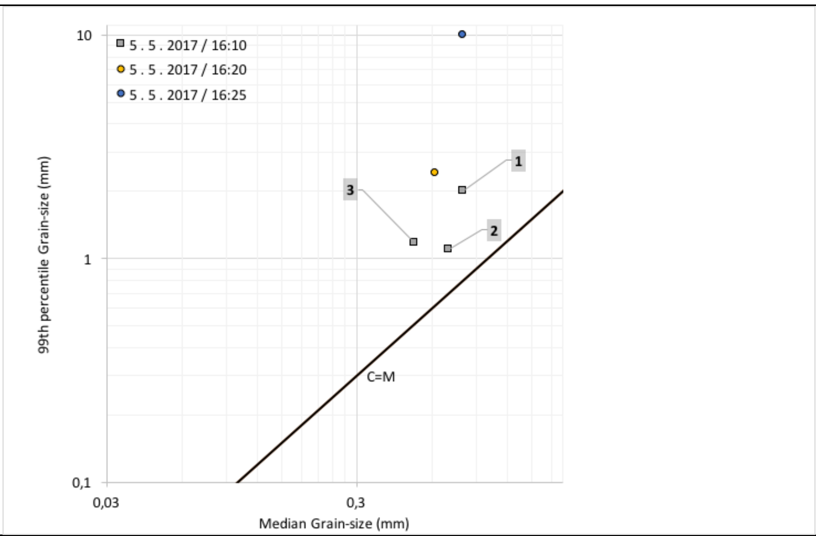
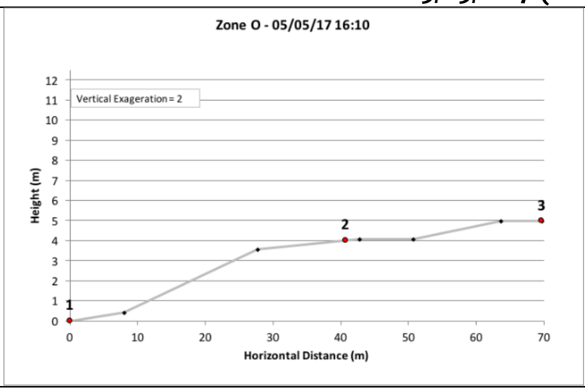
Zone O



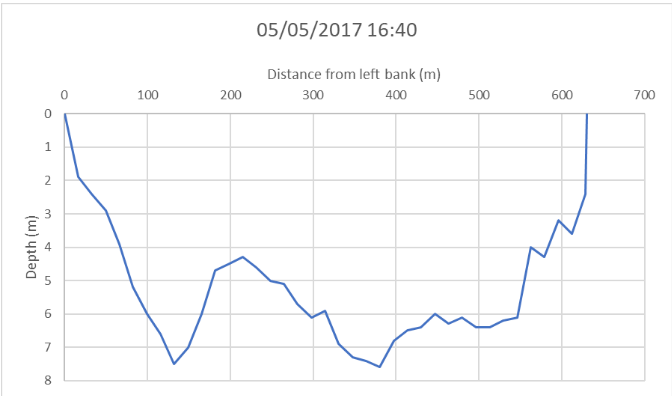
05/05/2017 (16:10) Recent bank



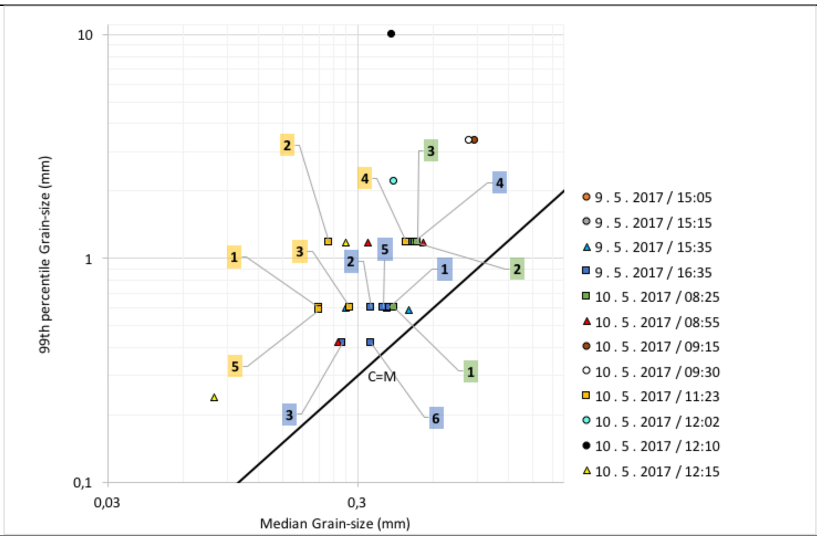
	M	C
1	800	2,000
2	700	1,100
3	510	1,180

Transect across a flat-lying bar built up after 2008. The cover of fine gravel is due to winnowing of the finer sand by wind action. The gravel is too coarse to be mobilised by wind and protects the underlying sand from additional erosion.

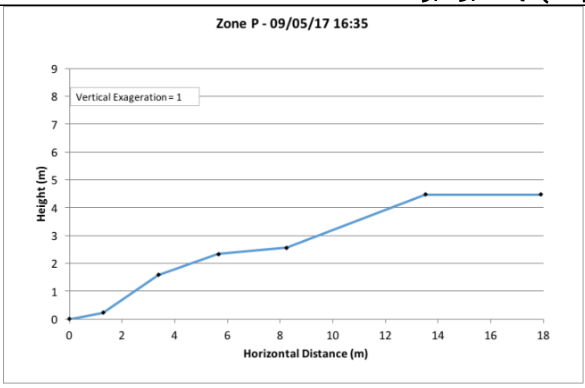
Channel cross-sections – Zone O (facing downstream)



Zone P

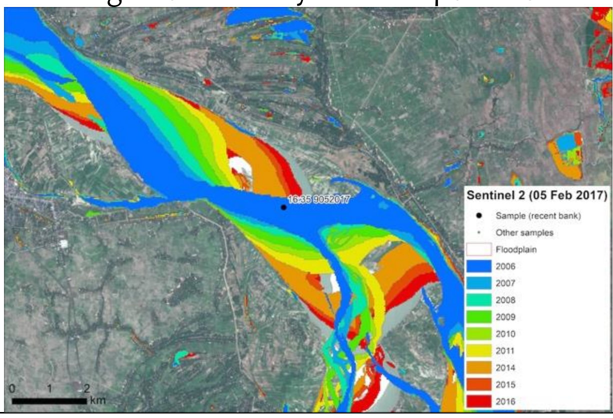


09/05/2017 (16:35) Recent bank



	M	C
1	400	600
2	340	600
3	260	420
4	500	1,180
5	380	600
6	340	420

Very active sector with lateral migration and very recent deposit from last flood.

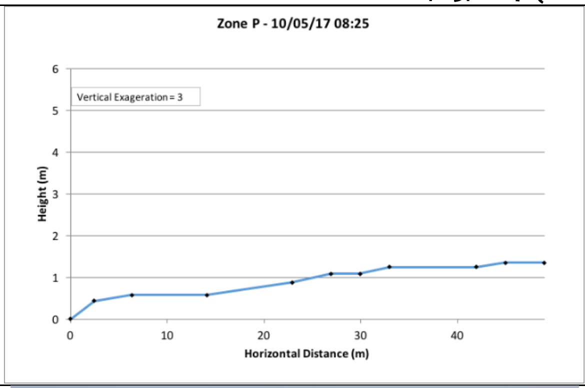


09/05/2017 (15:35) Old bank

	M	C	Location
1	270	600	7 m above water level
2	390	600	4 m above water level
3	480	590	0.3 m above water level

Eroded bank of a side channel abandoned after 1997. The sand core is topped by a thick layer of silty sand trapped by vegetation.

10/05/2017 (08:25) Recent bank



	M	C
1	420	600
2	510	1,180
3	520	1,180

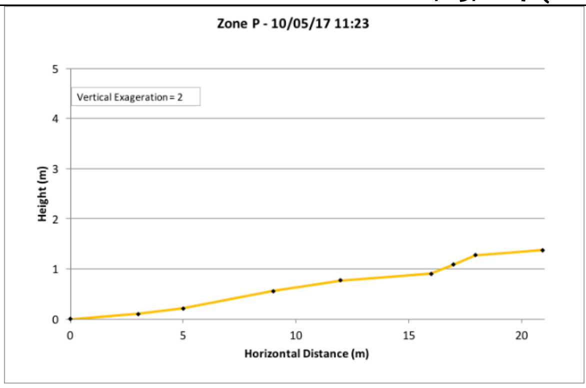
The bar supports aeolian dunes that are encroaching over the lateral, older swale on the right. This bar is only two years old, but the channel mobility is not very active in this place.

10/05/2017 (08:55) Old bank

	M	C	Location
1	250	425	4 m above water level
2	550	1,180	1.8 m above water level
3	330	1,180	0.2 m above water level

Eroded bank of a sandbar with sand at the bottom and silty sand in top layers. These layers were built up after 1992 and are currently eroding slowly.

10/05/2017 (11:23) Recent bank



	M	C
1	210	600
2	230	1,180
3	280	600
4	470	1,180
5	210	590

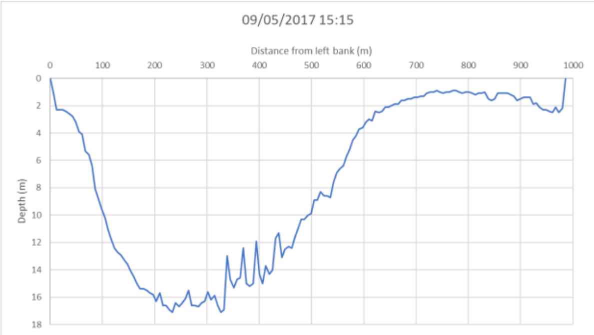
Stable bank of a pre-1988 sandbar.

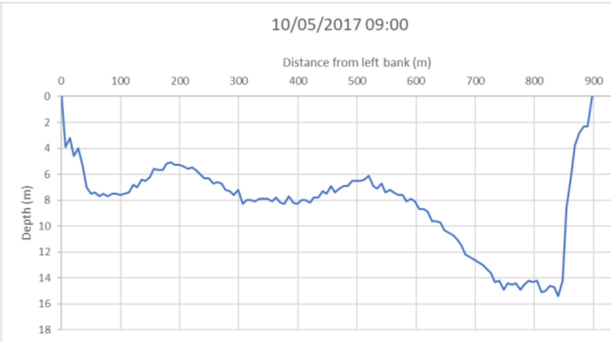
10/05/2017 (12:15) Old bank

	M	C	Location
1	80	240	0.1 m above the water level
2	270	1,180	Top of the bank

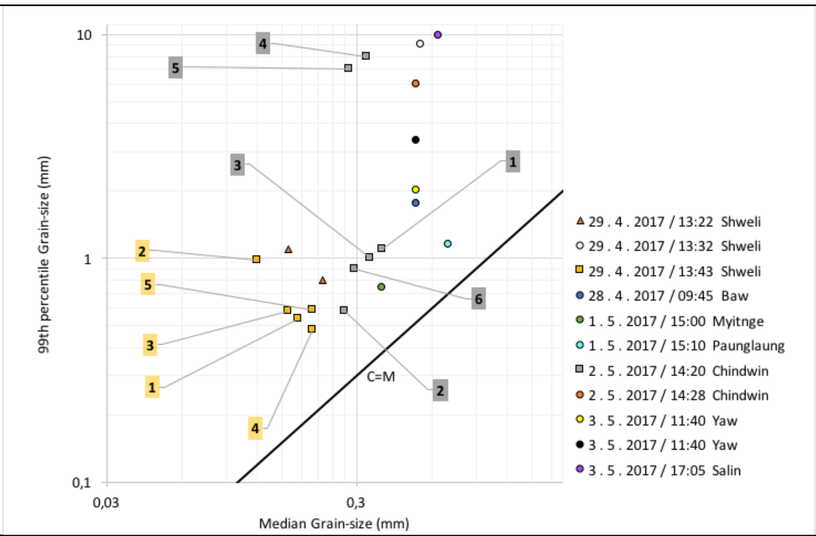
Bar platform built up after 2004 on a laterally aggrading stable island.

Channel cross-sections – Zone P (facing downstream)

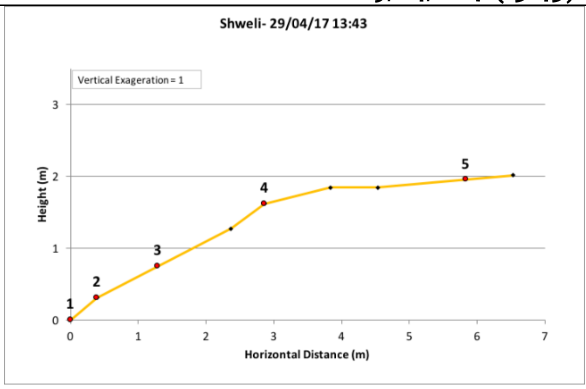




Tributaries (Shweli and Chindwin)



29/04/2017 (13:43) Shweli Recent bank



	M	C
1	175	540
2	120	980
3	160	580
4	200	480
5	200	590

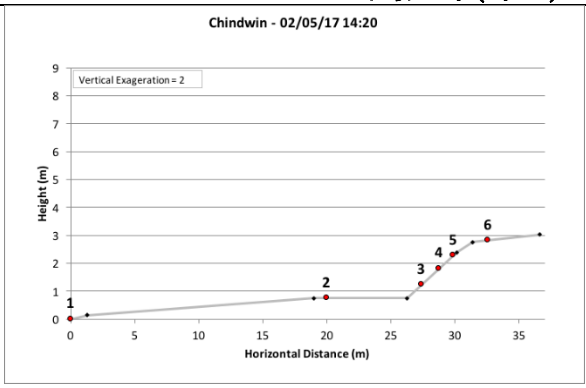
The left bank in Shweli was deposited after 2012 and is undergoing active lateral erosion. The lower Shweli shows a lot of change since the 1980s, likely due to hydropower development in the upper catchment.

29/04/2017 (13:22) Shweli Old bank

	M	C	Location
1	220	800	Water level
2	160	1,100	1 m above the water level

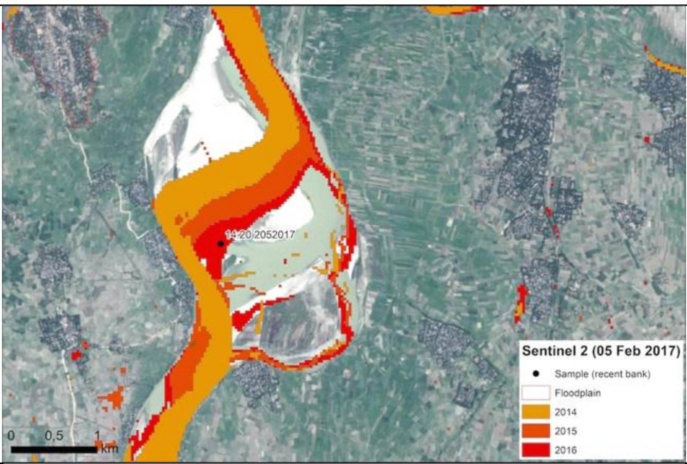
Left bank old deposit composed of sand at the base overlain by finer silty-sand. A similar layer is visible in the sand layers. The bar was deposited after 2009 and lateral erosion is active.

02/05/2017 (14:20) Chindwin Recent bank



	M	C
1	380	1,100
2	270	580
3	340	1,000
4	330	8,000
5	280	7,000
6	295	900

A 2 m thick deposit on the right bank of a mid-stream bar. The unit was shaped by the 2016 flood. Both deposition and lateral erosion are very active, as shown below.

	Annual channel migration at sampling site showing >100 m change per year.
	A flat mid-stream bar in the Chindwin composed of fine gravel and gravel (bedload of the channel) and sand platforms in the distance (graded suspension transported during floods).